ON-LINE REFRACTORY CONFIRMATION
FINAL REPORT

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DISCLAIMER

ABSTRACT

MSE Technology Applications, Inc. (MSE) conducted a test [U.S. Department of Energy (DOE) Award Number DE-FC26-02NT41584] to develop an innovative image recognition system that would monitor refractory surface conditions in a gasification chamber. This technology could provide early detection of internal degradation of the refractory lining without constant operator monitoring. The system would notify the operator of refractory problems by triggering an alarm. The software analyzing this system would send this alarm to the operator when the refractory change exceeds preestablished criteria. This particular portion of the testing demonstrated the capabilities and limitations of an MSE-designed high-temperature pinhole camera combined with Machine Vision software.

This test project explored the capabilities of the pinhole camera and software by demonstrating operating parameters in different test categories. MSE engineers selected the following test categories to show the flexibility and range of the on-line refractory confirmation system.

- Tape test – accuracy of area recognized as changed.
- Angle repeatability – measurement of error in repositioning refractory.
- Damage recognition at angles – damage detection at different angles.
- Low light capability – low light limit for camera and system.
- Intense light capability – intense light effect on damage recognition.
- Combustion light source – simulation of combustion process.
- Hot spot recognition – glowing red hot spot on refractory brick.
- Streaming image mode – neglect from temporary image interference.

The test results were more qualitative than quantitative in nature due to the fact that no specific criteria or operating conditions were established for the on-line refractory confirmation system. However, the results prove that the pinhole camera has a high enough resolution to recognize change in the refractory (Figure 1) under several adverse conditions. The compare program tuned with the selectable control parameters has the ability to process this image change into various pixel blobs and distinguish or isolate the significant changes from peripheral changes. These pixel blobs are directly proportional to the area changed, as shown in the tape test. The camera and compare program can recognize refractory change from several angles and a luminance from 3 cd/m^2 to intense light from an arc welder. The streaming image mode solves the problem of temporary image interference with a running average pixel count and provides extracted data samples for charting image change magnitude from a cycle with an adjustable frequency. This portion of the project indicates that the high-temperature camera and software system are ready for the next step of looking at actual gasification chamber refractory in operation.

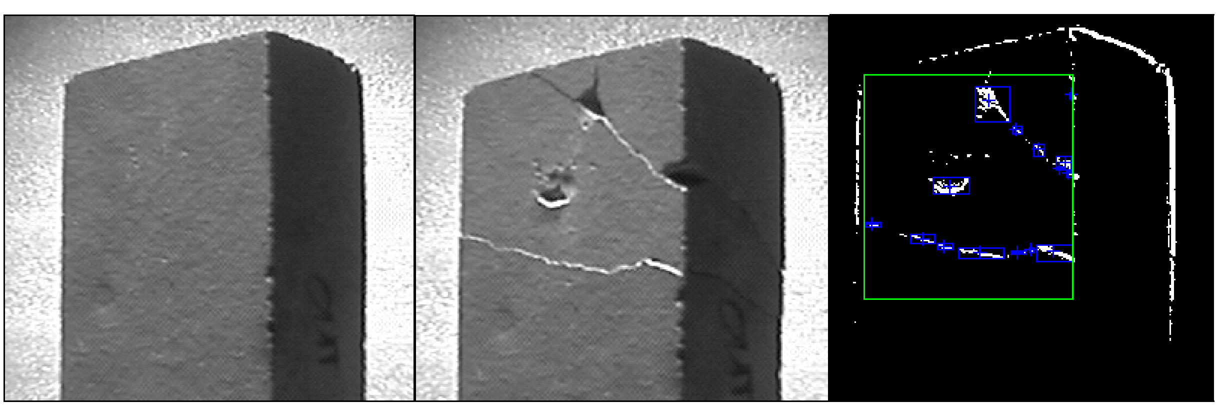

Figure 1. Refractory damage recognition.

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INTRODUCTION

Relatively short service life of the refractory lining inside a gasification chamber results from exposure to the extreme environment inside the operating gasifier. The best chromium-based refractory materials commercially available today have a predicted service life of less than 2 years. Gasifiers may either be dry ash or slagging systems with the most severe environment occurring in slagging gasifiers (Ref. 1). Refractory lining must withstand material challenges, such as sudden temperature variations, alternating oxidizing and reducing environments, corrosive slags and gases, erosion due to residual particulates, and high pressures. The image recognition system described in this report can provide constant real-time monitoring of the refractory lining and notify the operator of changes that may diminish the integrity of the gasification chamber.

MSE proposed a test (DOE Award Number DE-FC26-02NT41584) to develop an innovative image recognition system to monitor refractory surface conditions in a gasification chamber. This technology could provide early detection of internal degradation of the refractory lining without constant operator monitoring. The system would notify the operator of refractory problems by triggering an alarm. The software analyzing this system would send this alarm to the operator when the refractory change exceeds preestablished criteria. This particular portion of the testing demonstrated the capabilities and limitations of a high-temperature pinhole camera combined with Machine Vision software. These capabilities apply directly to actual gasification refractory monitoring.

This test project employed two separate technologies used with other MSE projects: 1) high-temperature, direct view pinhole charged-couple device (CCD) camera; and 2) Machine Vision technology and software. MSE developed the housing and cooling system that allows the CCD camera to withstand high temperatures. This camera system provided beneficial monitoring of the internal conditions in MSE's plasma furnace in the past withstanding operating temperatures of 1,650 °C. With another project, the Machine Vision technology and software provided MSE with the ability to remotely track aircraft launch bar status on U.S. Navy aircraft carriers. This remote confirmation of aircraft launch bar status can prevent aircraft from splashing into the sea at the end of the carrier due to improper or partial engagement. This launch bar project was successful through two phases of a Small Business Innovation Research program and is prepared to support full-scale deployment in Phase III.

This test concept joins the high-temperature CCD pinhole camera with the Machine Vision software to monitor refractory used in a gasification system. The CCD camera is the electronic "eye" and the Machine Vision is the "brains" of the system, which when combined, can see the refractory lining, make a decision about the status of the refractory, and notify the operator or control room that there may be a problem. This on-line refractory confirmation system would provide early detection of internal degradation or defects of the gasification chamber lining that may be problematic to the gasification process. These two separate technologies are a logical marriage for on-line refractory confirmation of a gasification system.

EXECUTIVE SUMMARY

MSE developed an innovative image recognition system to monitor refractory surface and internal conditions in a gasification chamber. The recognition system consists of a high-temperature CCD pinhole camera linked to Machine Vision and data acquisition software. This technology could provide early detection of internal degradation of the refractory lining without constant operator monitoring.

This test demonstrated excellent qualitative results for using this high-temperature camera and software to conduct on-line refractory confirmation in a gasification chamber. The test procedure subjected the camera and software to several vessel configurations with the intent of exploring system adaptability and limitations. The following test categories established system potential.

- Tape test – accuracy of area recognized as changed.
- Angle repeatability – measurement of error in repositioning refractory.
- Damage recognition at angles – damage detection at different angles.
- Low light capability – low light limit for camera and system.
- Intense light capability – intense light effect on damage recognition.
- Combustion light source – simulation of combustion process.
- Hot spot recognition – glowing red hot spot on refractory brick.
- Streaming image mode – neglect from temporary image interference

The tape test proved that the compare program recognized changed regions, or blobs, that were directly proportional to the relative surface area undergoing change. These blobs are made of individual pixels linked together. The total pixel count doubled, for example, when the area changed doubled. This size recognition ability could actually measure the amount of surface area changed on the refractory.

The angle repeatability run simply showed that the steel plate jig holding the refractory bricks in alignment to the camera allowed good repeatability. This eliminated any error that could be attributed to repositioning refractory brick for image grabbing.

The damage recognition at angles looked at refractory brick at 30-, 45-, 60-, and 90-degree angles from the camera line of sight. In this particular scenario, the best camera angle for refractory damage recognition occurred at 45 degrees. However, light source positioning influenced the optimum viewing angle. It is advantageous for the damaged area to appear larger or more pronounced due to a shadowing effect.

The low light capability test found that the camera and compare software were capable of detecting damage to the refractory in very low light conditions. The system was able to find a small crack in the refractory brick at a luminance of approximately 3 cd/m^2.

The system was able to recognize a small crack in the refractory under an arc welding rod light source but with some difficulty. A combination of the intense light and the dark filter probably caused the crack in the brick to fade out more easily. However, the system had no problem finding a more pronounced change, such as slag accumulation.

An oxy acetylene rosebud flame burning between the camera and the refractory provided simulation of a combustion process. The compare program region of interest (ROI) capability allowed the software to focus on the brick surface eliminating the flame region of the picture and recognizing only the surface change of the refractory.

A glowing hot spot on the refractory showed up just as well as any other type of surface change. Enough gray-level contrast, attributed to color change in the refractory brick, allowed the compare program to easily recognize the hot spot area.

The streaming image test provided excellent data results for demonstrating how a series of images can be averaged over time eliminating temporary image interference or false fluctuations. The program uses a running average to diminish data spikes that could result from temporary obstructions, such as a smoke cloud or debris, in the gasification chamber. This same concept could eliminate light fluctuations reflecting off the refractory wall and look only at the mean in the data resulting from refractory surface degradation. This streaming image cycle frequency is variable from fractions of a second to hours and days.

This was a successful test in regard to exploring the capabilities and limitations of the CCD pinhole camera coupled to the frame grabber and compare program. The camera has a high enough resolution to recognize change in the refractory under several adverse conditions. The compare program tuned with the many flexible parameters has the ability to process this image change into various pixel blobs and distinguish or isolate the significant changes from peripheral changes. This portion of the project indicates that the high-temperature camera and software system are ready for the next step of looking at actual gasification chamber refractory in operation.

EXPERIMENTAL

MATERIALS AND EQUIPMENT

The test equipment for this project included four main components. The components were:

- cylindrical steel test vessel;
- high-temperature CCD camera;
- personal computer (PC) with Machine Vision software; and
- refractory brick test media.

The test vessel (Figure 2) is a 1.2-m tall, 1-m diameter, 9-mm thick cylindrical steel fixture mounted in a tubular frame. This vessel is versatile and may simulate many different conditions of no light, ambient light, intense light, and light from a gasification or combustion process. A 500-W halogen light mounted to the top of the vessel and controlled by a metered rheostat allowed variable and repeatable light levels. An oxy acetylene light source was installed in the vessel to simulate conditions similar to a gasification chamber. Finally, an arc welder operated inside this vessel emitted an intense light for camera testing. The vessel has one main hatch entrance and several side ports for test monitoring equipment. This vessel could possibly operate as an incinerator or gasifier if fitted correctly.

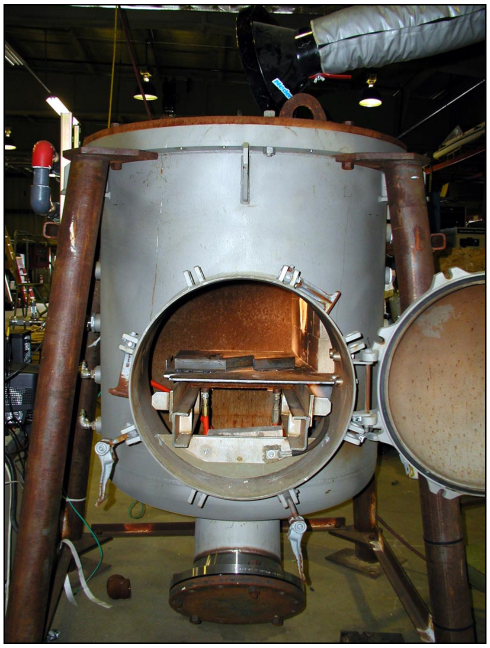

Figure 2. Test vessel.

The high-temperature CCD camera consists of an off-the-shelf miniature or pinhole video camera and a liquid-cooled housing designed by MSE. The camera has a 1/3-in. color 512 X 492 pixel image with a 1/100,000 shutter speed and auto iris. The camera body is 20 mm in diameter and 57 mm long with a 3.6-mm, 80-degree lens (Ref. 2). MSE purchased the PC79 series pinhole camera (Figure 3) from Super Circuits (www.supercircuits.com) who claim it is one of the world's smallest CCD video cameras. The camera housing (Figure 4) consists of a double-wall tubular stainless steel jacket that protects the camera from high temperatures up to 1,650 °C. The camera housing can hold different lens filters and also has small voids in front of the lens to allow gas purging of debris that may accumulate. Normally, water flows through the housing jacket to maintain a cool operating environment for the pinhole camera. MSE currently uses this camera housing in their plasma furnace system for monitoring internal conditions. This camera housing slides through a locknut collar (Figure 5) for penetration depth adjustment and is adaptable to many types of fittings.

Figure 3. PC79 series pinhole camera.

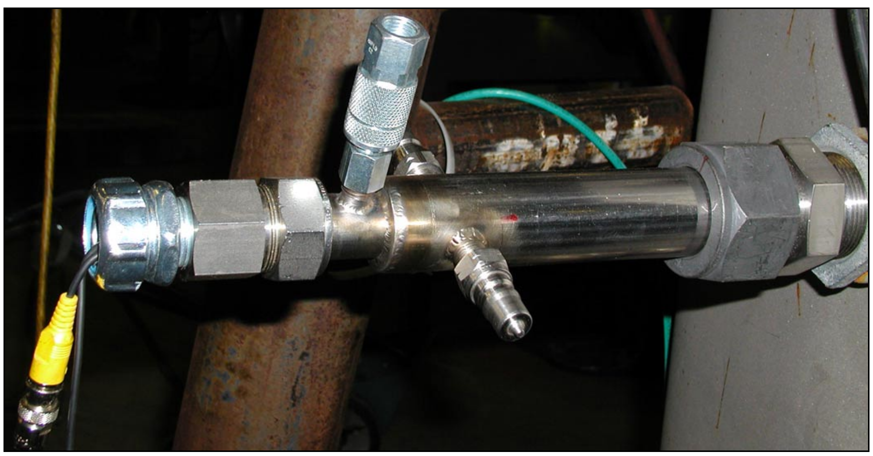

Figure 4. Camera housing.

Figure 5. Camera housing sliding through locknut collar.

A Dell® PC (Figure 6) with a frame grabber card and Machine Vision software served as the information gathering and analysis portion of the experiment. This is a new model computer with a 2.4-GH processor, 128-MB random access memory, and 100-GB hard drive. The computer ran on Microsoft® Windows 2000 and used an image recognition program (developed by Lecky Engineering) that was based on visual basic code. The frame grabber card is a Matrox Orion® video capture card that can manage up to eight video inputs with a 32-MB graphic and video buffer (Ref. 3).

Figure 6. Dell PC.

The test media consisted of standard 230- X 115- X 76-mm clay firebrick (Figure 7.). These general fireclay bricks are made of various fireclays and calcined chamotte. General fireclay bricks find the widest application among various kinds of industries. Therefore, the fireclay bricks are suited for use in high-temperature, high-pressure operating furnaces, such as blast furnaces. These firebricks allowed great flexibility in testing different conditions for the on-line refractory test with ease of placement, actual damage simulation, and reaction to high-temperature conditions. These bricks simulated, as closely as possible, refractory that may be found inside a gasification chamber.

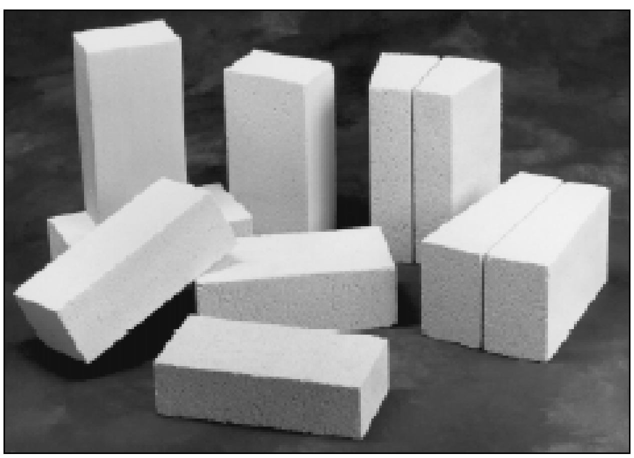

Figure 7. Standard 230- X 115- X 76-mm clay firebrick.

METHODS

This project looked at several test media configurations by varying parameters, such as camera angle, light intensity, refractory damage, temperature, and temporary obstruction problems. MSE engineers selected these different configurations to test the limitations and capabilities of the camera and software. These configurations may not necessarily represent accurate gasification chamber conditions. However, the conditions simulated, as closely as possible, different scenarios that may be encountered in an incinerator or gasification chamber. The test run categories included the following configurations.

- Tape test – accuracy of area recognized as changed.
- Angle repeatability – measurement of error caused by moving refractory bricks in steel plate angle jig.
- Damage recognition at angles – how well system detected refractory damage at different angles.
- Low light capability – low light limit for camera and system.
- Intense light capability – intense light effect on damage recognition.
- Combustion light source – simulation of combustion process.
- Hot spot recognition – glowing red hot spot on refractory brick.
- Streaming image mode – neglect from temporary image interference and extracting data for chart record averaging.

SOFTWARE DESCRIPTION

Before explaining each of these test runs in detail, it is important to understand the Windows-based interface to the Machine Vision software and what controls were used to tune the software. The Lecky Engineering Machine Vision package contains a large library of applications that may be linked together to form a tailored program that is project specific. The following paragraph explains what parts of this Machine Vision library the MSE engineers selected for the Windows interface to run this test.

The Windows interface screen (Figure 8) the MSE engineers created for this test was simple and concise, but effective. This is a common-looking Windows screen with tabs, buttons, information boxes, and a selection list. Although the window lacks some box description labels, this program could be easily operated by anyone familiar with mouse functions on a Windows screen.

Figure 8. Windows interface screen.

The frame grabber program records images at the click of the "Record Image" button and stores them as bitmap (BMP) files similar to any digital camera. These images transfer to the compare program and appear in the "Image One" and "Image Two" blocks. These images are now selectable for comparison. By clicking on the "First Image" tab and then the desired image file from the "Image One" block, the first image loads to the compare program. The same procedure applies to load image two. Next, by clicking on the "Image Difference" tab and then the "Compare" button, the software shows any difference in pixel values from image one to image two (Figure 9).

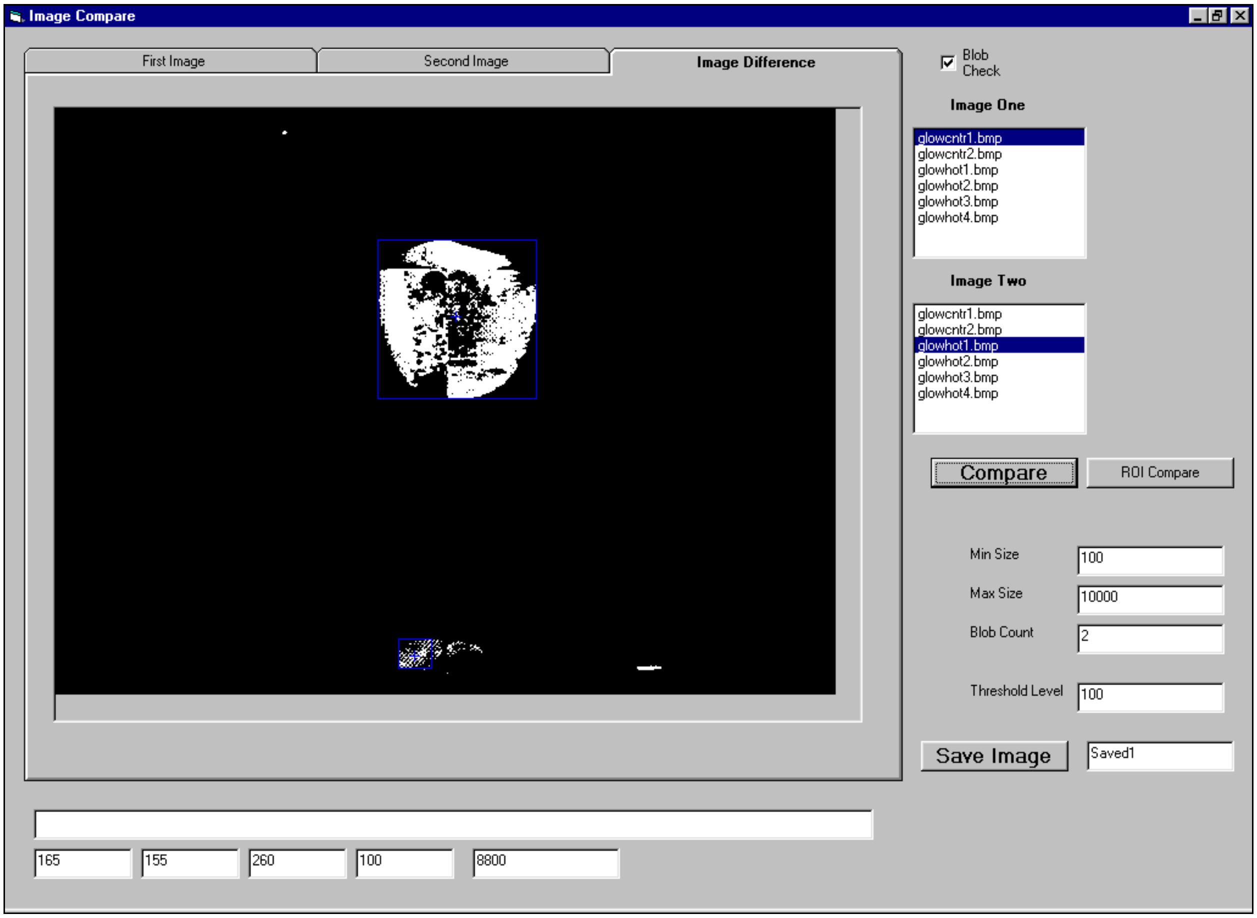

Figure 9. Software showing difference in pixel values from image one to image two.

The program groups pixel changes together and calls them blobs. These blobs are outlined in blue rectangles (Figure 10). Consequently, one of the key tuning controls of this program is what size of a blob the compare program will recognize. The user establishes this blob size by selecting the "Min Size" and "Max Size" numbers in the control blocks toward the bottom right of the window. These size blocks determine the number of pixels linked together to form a blob. The "Blob Count" box indicates the number of blobs recognized as changed within the "Min Size" and "Max Size" criteria. The fifth from the left bottom information block reports the total number of pixels within all of the recognized blob areas.

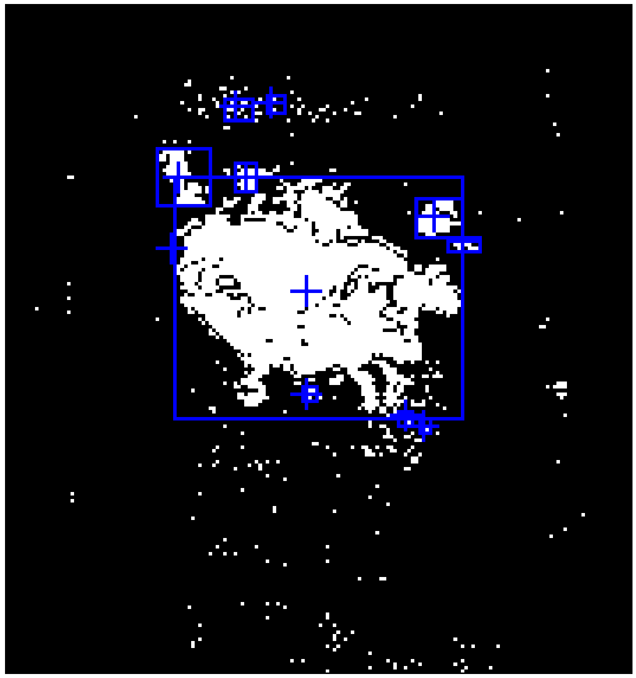

Figure 10. Image showing blobs outlined in blue rectangles.

The compare program is also capable of looking at only an ROI within the entire field of view. The compare program employs images loaded in the same manner as previously explained with the "Image One" and "Image Two" tabs. However, after clicking on the "Image Difference" tab, the user may choose the "ROI Compare" button. This button implements a comparison only in the specified ROI outlined in the green rectangle (Figure 11). The user presets the region of interest by entering coordinates in the first four bottom information blocks in the window. Blocks 1, 2, 3, and 4 are the "x," "y," "Δx," and "Δy" coordinates, respectively.

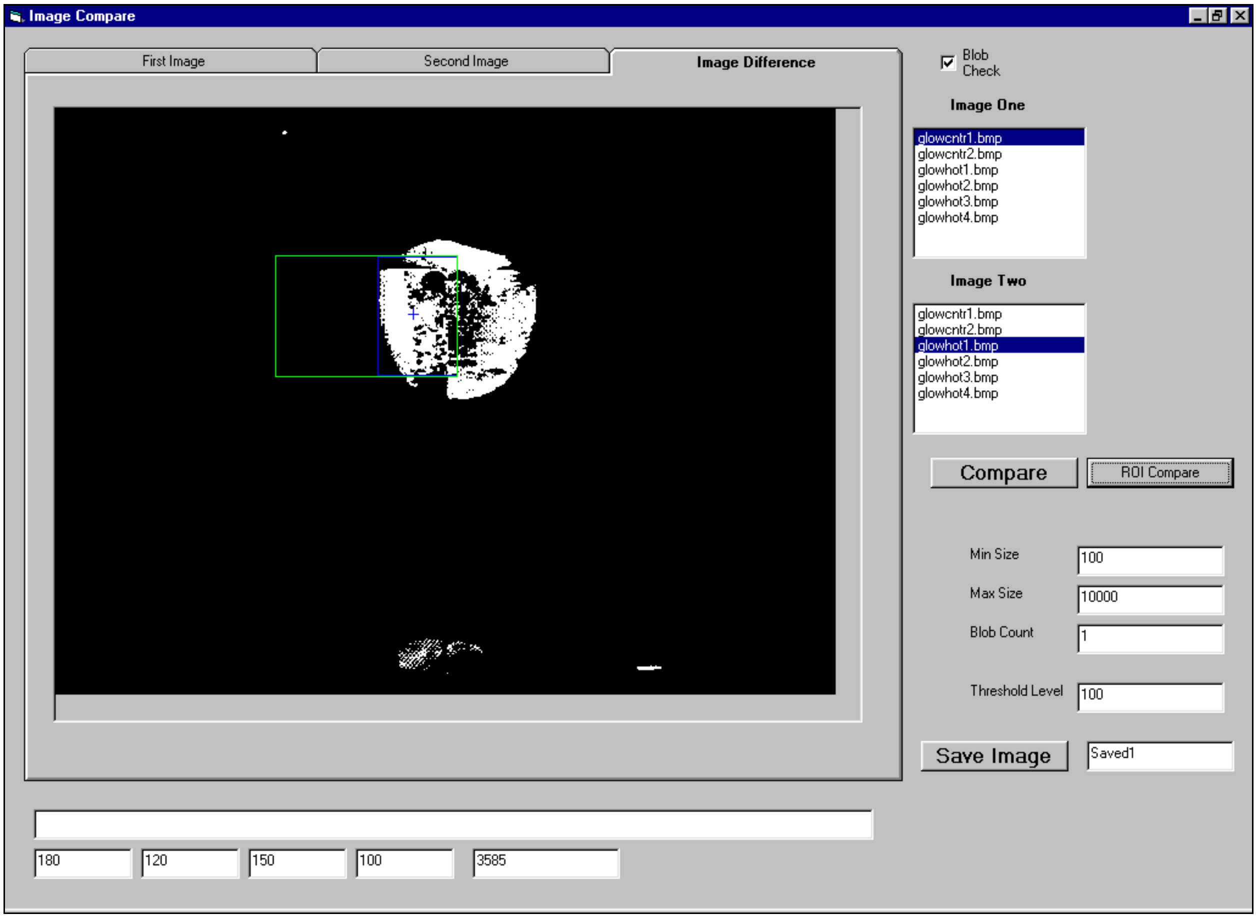

Figure 11. Software showing comparison only in specified ROI outlined in green rectangle.

MSE engineers also tailored this software to look at a streaming image, which is really a series of images taken at a desired frequency. The frame grabber program starts recording these images at the click of the "Record Image" button and stops recording at the second click of this button. The compare program then takes an average blob count for the entire series of images. These image series average blob counts cross over to the compare program and load in the same manner as individual images. The image series can cycle at any frequency and run for any length of time depending on the requirements. This average blob count for the entire series negates any temporary image interference.

Some other features of this interface window are the "Threshold Level" button and the "Save Image" button. The threshold level is a parameter that determines for a given gray level which output pixels are turned "on" and which remain "off." The compare program converts images to a series of monochrome gray-level pixels ranging from 0 (black) to 255 (white) (Ref. 4). Each pixel in the BMP is defined by an 8-bit B and carries a value from 0 to 255. For any given output pixel that has an incoming gray level value that is less than the corresponding threshold level value, the pixel is set black. Conversely, a light area (high gray value) greater than or equal to the threshold value will show white. Overall, this feature is similar to a contrast control knob on a television monitor.

The "Save Image" button records the comparison image and pertinent information to a data file. The data saved could include information from any of the control blocks, such as "Min Size," "Threshold Level," and so on. The long block above the ROI coordinate blocks (toward the bottom of the window) allows comments to describe the saved image. This data can provide numerical information to other programs, like Excel, for statistical analysis, charting, or other things.

TAPE TEST

This test quantified the blob count area and tested image change recognition in both light and dark pixel changes. The frame grabber recorded images of a plain firebrick at a 90-degree angle with different lengths of black tape added (Figure 12).

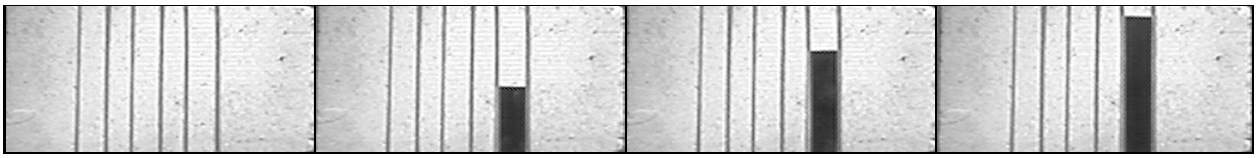

Figure 12. Frame grabber recorded images of plain firebrick at 90-degree angle with different lengths of black tape added.

The tape was added to the same brick in lengths of 51, 76.5, and 102 mm, which correspond to areas of 1, 1.5, and 2, respectively. The test runs included all possible brick image combinations for comparison resulting in a total of 16 comparisons. The comparison combinations purposely had repeated areas in reverse to verify blob area changes from both light-to-dark and dark-to-light image difference. This was a good starting point in determining whether the compare program was responding in a predictable and logical manner.

ANGLE REPEATABILITY

This test determined how much error might be involved in placing a brick back in its original position on the steel plate jig. The frame grabber recorded an image of the firebrick at each angle predetermined by the steel plate jig angle iron. The same firebrick rotated through the preset angles a second time and the frame grabber recorded this image for comparison. An MSE engineer placed the brick, as carefully as possible, in the exact position at each angle station on the jig. The compare program looked at the two images at each angle to determine how much change in pixel format resulted when the brick was repositioned in the jig.

DAMAGE RECOGNITION AT ANGLES

The camera could possibly encounter difficulty recognizing certain refractory damage at certain angles due to light reflection and shading. Of course, this has a great deal to do with lighting and severity of damage. The damaged area may be shaded due to angle variation either making the damaged area more recognizable or completely hidden. A steel plate with welded angle iron worked as a jig (Figure 13) and determined the position of the firebrick with respect to the camera line of sight at 90-, 60-, 45-, and 30-degree angles. For this test, the frame grabber recorded images of an undamaged brick at each preset angle on the steel plate jig. This same brick received the prescribed damage and rotated through the different angles for the frame grabber to record an image of the brick after damage. The sort of firebrick damage selected for these runs included cracks, erosion, and edge degradation. The compare program then looked at the undamaged brick image in contrast to the damaged brick at each angle using the ROI compare method (Figure 14) to focus only on the surface of the brick. This neglected any image change caused by the shadow effect from the side of the brick. The light source remained constant in position and intensity.

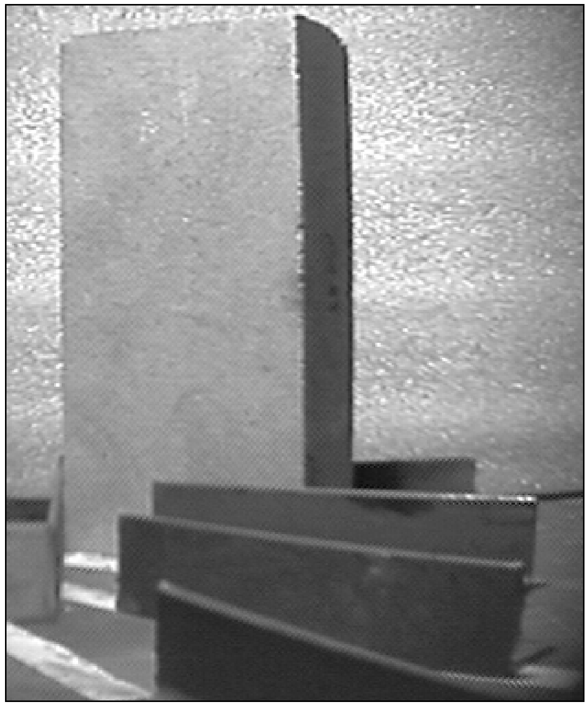

Figure 13. Steel plate with welded angle iron working as jig.

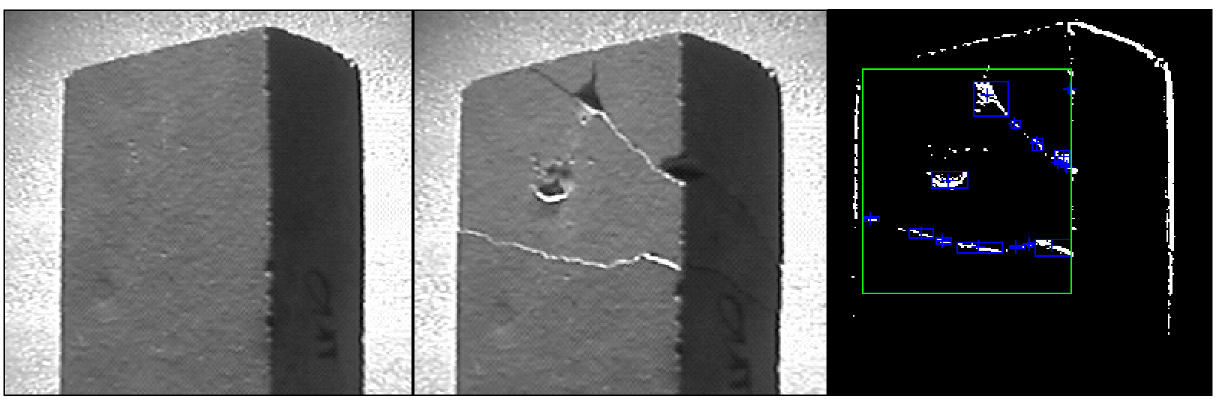

Figure 14. Undamaged brick, cracked brick, and ROI compare model.

LOW LIGHT CAPABILITY

The manufacturer claims this CCD pinhole camera will function at a minimum illumination of 0.1 lux. This is the illumination produced by a luminous flux of one lumen falling perpendicularly on a surface of 1 m^2, also called a meter candle (Ref. 5). The floodlight (Figure 15) provided a constant illumination of the bricks in all previous tests from the top plate of the vessel. This test gradually lowered the intensity of the 500-W light source in measurable increments until the pinhole camera and frame grabber software would no longer recognize change in the refractory firebrick. A standard photography light meter measured the light intensity or illumination inside the test vessel after each increment change. A large rheostat with a numbered dial (Figure 16) allowed the light intensity to vary with accurate repeatability. The frame grabber recorded an image of an undamaged firebrick at the metered light setting. An MSE engineer cracked this same brick and recorded the image with the frame grabber under the previously determined light setting. The rheostat reduced the light intensity in increments until the pinhole camera and compare program could no longer find the cracked surface. A firebrick covered in simulated slag went through this same test procedure.

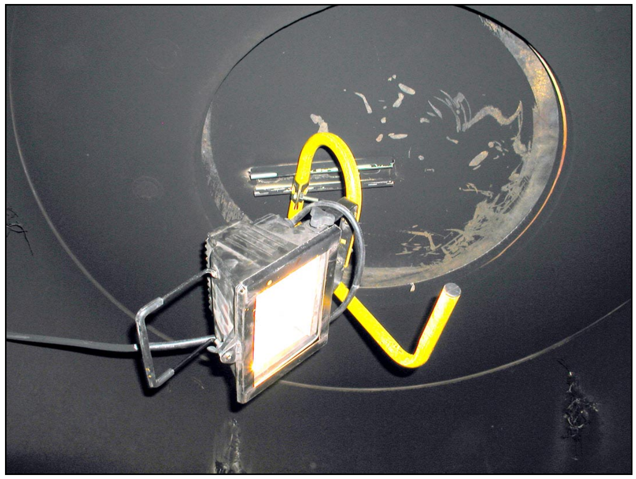

Figure 15. Floodlight – provided constant illumination of bricks from top plate of vessel.

Figure 16. Large rheostat with numbered dial – allowed light intensity to vary with accurate repeatability.

INTENSE LIGHT CAPABILITY

An arc welding rod activated inside the chamber on the steel plate jig directly in front of the firebrick provided fairly intense light to the CCD pinhole camera. The camera housing accepts filters fitted in front of the lens to attenuate light. These filters are Tech Spec™ reflective neutral density filters (Figure 17), which are often used in laser and photometer applications where excessive power can cause inaccurate results (Ref. 6). A Number 2 optic density filter with 1% transmission and 44% absorption shielded the CCD camera from the intense arc welder light. The frame grabber recorded four images of a perfectly good brick under the intense light conditions at increments of approximately 5 s. This same firebrick received characteristic change in the form of slag or slag deposit and a small crack. The frame grabber again recorded images at increments of approximately 5 s. The compare program looked for pixel change from the undamaged brick under the ROI method (Figure 18) to eliminate interference from arc welding rod debris.

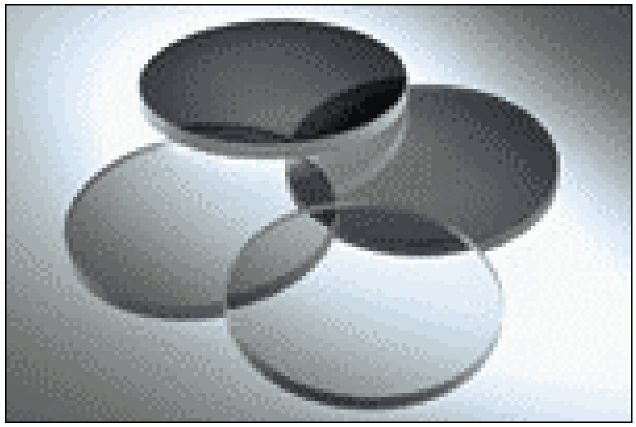

Figure 17. Tech Spec reflective neutral density filters.

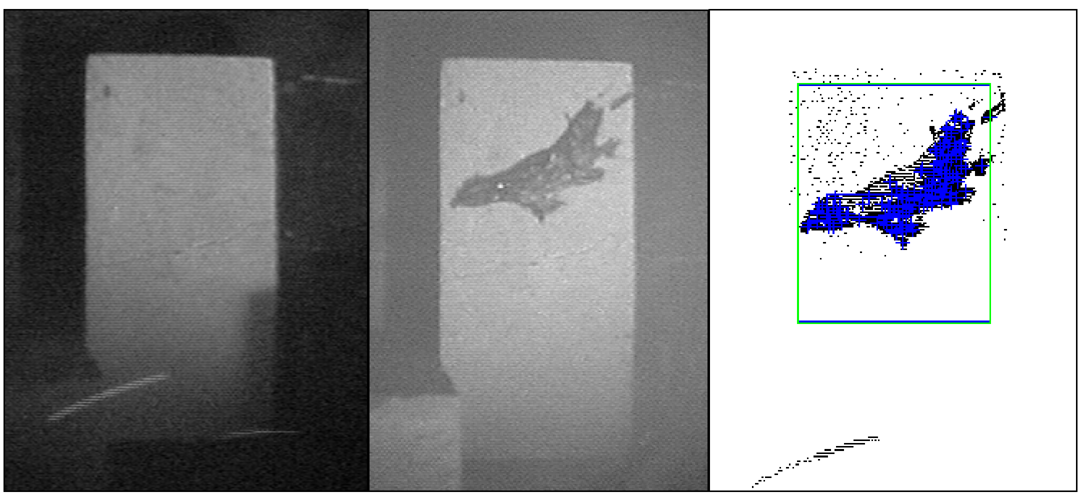

Figure 18. Bare brick, buildup on brick, and ROI compare model.

The CCD camera and frame grabber recorded these images with a Number 2 neutral density filter lens and the arc welder rod as the only source of light.

COMBUSTION LIGHT SOURCE

A large oxy acetylene torch tip (rosebud) (Figure 19) inserted through the side port above the CCD camera provided a large flame inside the chamber, just in front of the bricks. The idea behind this test was to determine how well the camera and software would recognize refractory change in a flame sort of light. The frame grabber first recorded several images of the firebrick with no physical change in time increments of approximately 10 s. The compare program determined how much blob change recognition occurred just from the flickering light source. Next, the frame grabber recorded images from an undamaged brick and then the same brick damaged to run in the compare program. Again, the compare program ran in the ROI mode (Figure 20) because the flame was in the picture and caused too much change.

Figure 19. Oxy acetylene torch tip (rosebud) – inserted through side port above CCD camera to provide large flame inside chamber.

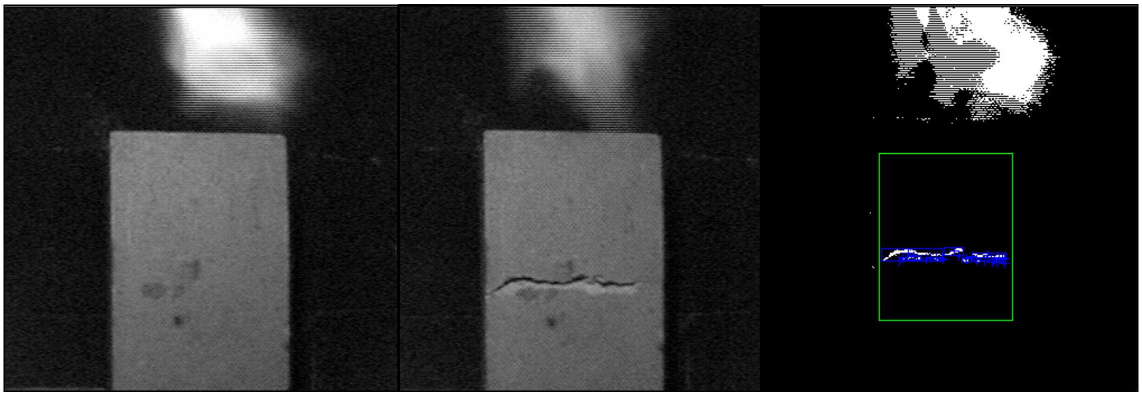

Figure 20. Undamaged brick, cracked brick, and ROI compare model.

The CCD camera and frame grabber recorded these images without a filter and the oxy acetylene flame as the only source of light.

HOT SPOT RECOGNITION

The refractory lining of an incinerator or gasification chamber may develop a hot spot. The refractory could have a region of much higher temperature than its surroundings. The oxy acetylene torch, capable of producing temperatures of 3,316 °C, heated a spot on a firebrick wall inside the test vessel until the brick was glowing red. The frame grabber recorded several images of the brick wall before and after the hot spot (Figure 21). The image with the hot spot has the oxy acetylene heat source removed.

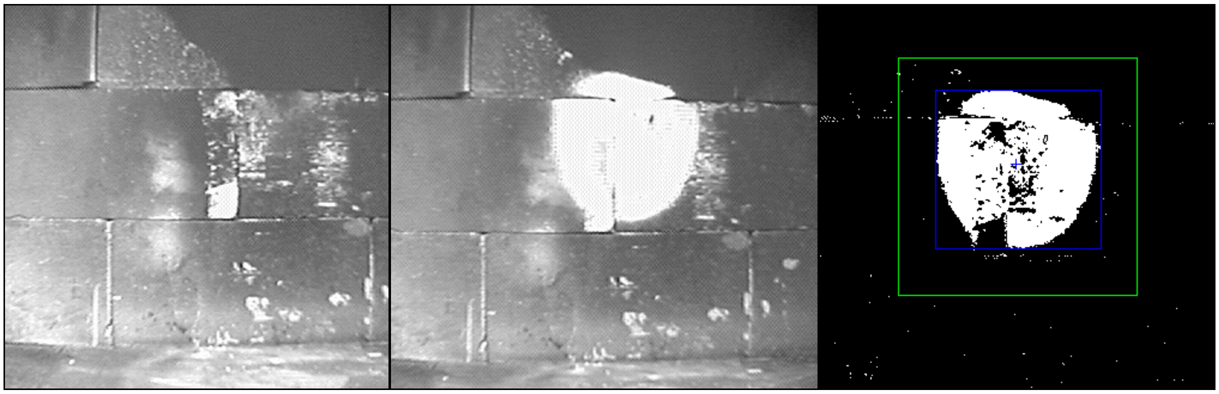

Figure 21. Refractory, hot spot, and ROI compare model.

The CCD camera and frame grabber recorded these images under the highest setting of the 500-W halogen light immediately after removing the oxy acetylene heat source.

STREAMING IMAGE MODE

There may be occasions when the on-line refractory confirmation system may encounter temporary image interference. An object or thick smoke could temporarily obstruct the camera field of view. MSE engineers have approached this problem by operating the frame grabber in a streaming image mode. The frame grabber recorded a series of images of the refractory wall at four frames per second for 3 min. During this series, a black 2 X 4 passed in front of the wall for approximately 3 s. creating a temporary interference. The frame grabber sent images to the compare program that averaged the change in pixel count over the entire series eliminating the short interference. The next test run included the black 2 X 4 entering the field of view and remaining for the rest of the run cycle simulating permanent change. The last test run in this mode looked at a slowly growing damaged area simulating refractory erosion. The objective behind this image averaging ability over time is to eliminate any extreme fluctuations or interference creating a spike in the pixel count and triggering a false alarm.

RESULTS AND DISCUSSION

TAPE TEST

The tape test provided a quantitative and qualitative initial checkout of the compare program. Different lengths of black tape tested the compare program for a fairly accurate area recognition and pixel contrast (Figure 22 and Table 1). The control program tuning parameters were Min Size = 100; Max Size = 10,000; and Threshold Level = 60.

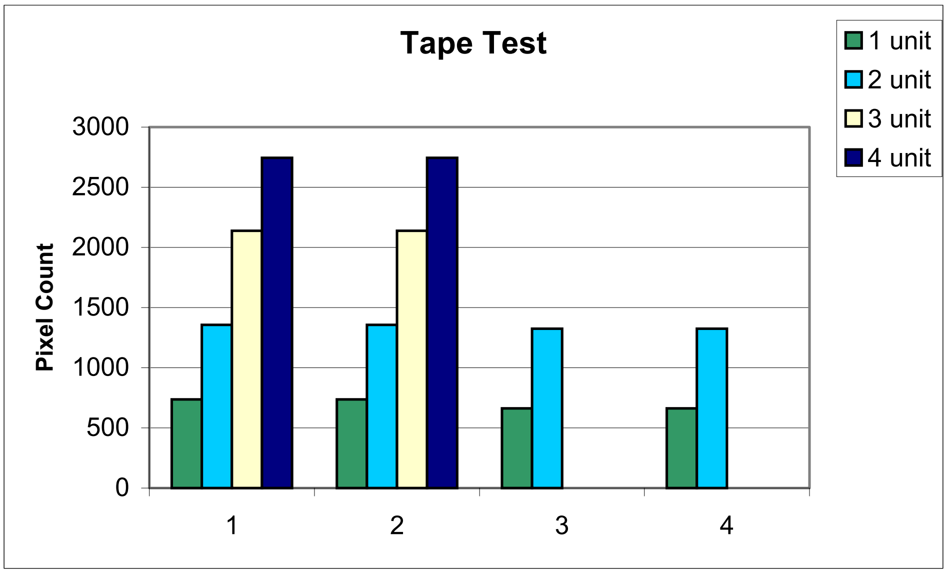

Figure 22. Area recognition and pixel contrast comparison.

Table 1. Area recognition and pixel contrast comparison.

IMAGE 1	IMAGE 2	BLOB	Δ AREA	PIXEL
0	0	1	0	0
0	2	1	2	1,356
0	3	1	3	2,138
0	4	1	4	2,745
2	0	1	-2	1,356
2	2	1	0	0
2	3	1	1	738
2	4	1	2	1,324
3	0	1	-3	2,138
3	2	1	-1	738
3	3	1	0	0
3	4	1	1	661
4	0	1	-4	2,745
4	2	1	-2	1,324
4	3	1	-1	661
4	4	1	0	0

This tape test simply shows that the pixel count is relative to the area change and that it makes no difference if the change occurs from dark to light or light to dark. For example, when the area change is roughly doubled, the pixel count is doubled. In Table 1, 0 → 2 = 1,365 and 0 → 4 = 2,745. This is relatively double the pixel count for double the area. If the tape were more precise in exact lengths, the pixel count would also be more precise. This test also confirms that the compare program makes no distinction between dark or light image changes. Going from 0 → 2 = 2 → 0 or 2 → 4 = 4 → 2, the pixel counts are identical. The program recognizes change either in adding tape or subtracting tape.

Both of these area difference recognition attributes could be important for monitoring refractory inside a gasification chamber. The relative area pixel relationship could be important in recognizing a certain size of a particular flaw in the refractory. In fact, this pixel count could be converted to units of length for area or height and length. The recognition of area change from light to dark or dark to light may be important depending on the condition of the refractory inside the chamber. The refractory could be clean and light colored or dark. Either way, the compare program will recognize change to the refractory.

ANGLE REPEATABILITY

The steel plate jig worked well for guiding the bricks to a precise position for each placement. This angle repeatability assurance eliminated error from repositioning a firebrick each time for image comparison. The position consistency (Table 2) is evident in the following data from the compare program.

Table 2. Position consistency comparison.

IMAGE 1	IMAGE 2	BLOB	PIXEL
30A	30B	35	154
45A	45B	0	0
60A	60B	0	0
90A	90B	0	0

The compare program tuning parameters were extremely low for this test run to allow some recognition of change resulting from brick placement (Min Size = 2; Max Size = 10,000; and Threshold Level = 30). These parameters are lower than any test run for the damage recognition at these same angle configurations. The 30-degree angle is the only instance of recognizable change. This change recognition at the 30-degree angle is partially due to the fact that the jig brings the brick closer to the camera as the angle decreases. Also, there is naturally more side exposure of the brick as the angle decreases. It is important to notice that most of the pixel change recognition occurred on the edge of the brick. This undesired pixel change disappeared with the ROI capability (Figure 23) of the compare program by zeroing in on the face of the brick and neglecting the edges.

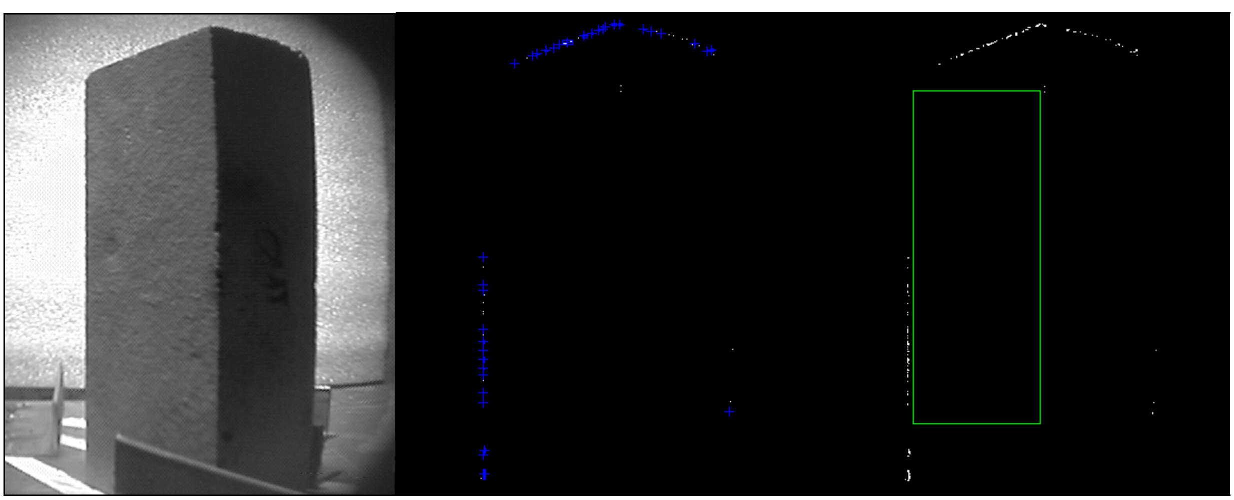

Figure 23. Image at 30 degrees, compare model (pixel = 154), and ROI compare model (pixel = 0).

The results of this test run show that with the steel plate jig, error due to brick placement is minor. The ROI feature of the compare program eliminated any pixel recognition due to brick placement. This would not be a factor for on-line refractory confirmation of a gasification chamber when the camera and refractory maintain a static position. However, for this test, it was important to establish the amount of error that may be imparted from repositioning of the firebricks.

DAMAGE RECOGNITION AT ANGLES

The compare program supplied the following data for refractory crack (Table 3), erosion (Table 4), and edge (Table 5) damage (Figure 24). The three test runs maintained the same compare program tuning parameters (Min Size = 5; Max Size = 10,000; Threshold Level = 50).

Table 3. Crack damage run.

IMAGE 1	IMAGE 2	BLOB	PIXEL	% DIFF
cntr90	crck90	12	374	
cntr60	crck60	13	438	14.61
cntr45	crck45	17	833	55.10
cntr30	crck30	18	753	50.33

Table 4. Erosion damage run.

IMAGE 1	IMAGE 2	BLOB	PIXEL	% DIFF
cntr90	por90	11	2,070	
cntr60	por60	8	2,340	11.54
cntr45	por45	14	2,943	29.66
cntr30	por30	18	2,863	27.70

Table 5. Edge damage run.

IMAGE 1	IMAGE 2	BLOB	PIXEL	% DIFF
cntr90	edg90	27	1,315	
cntr60	edg60	21	1,675	21.49
cntr45	edg45	37	2,845	53.78
cntr30	edg30	42	1,430	8.04

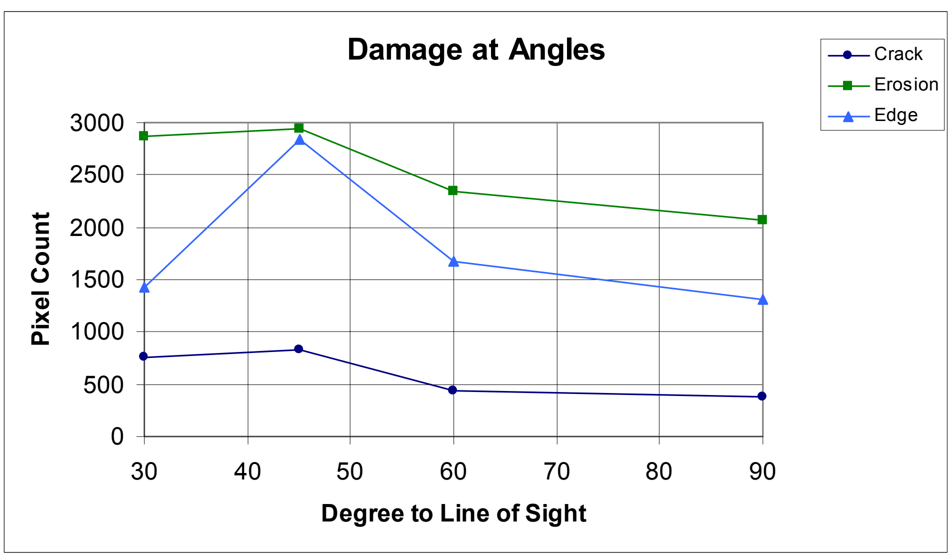

Figure 24. Crack, erosion, and edge damage at 30-, 45-, 60-, and 90-degree angles.

The important result from this data is that the overall trends for each damage type are similar. The trends suggest that the 45-degree position creates the highest pixel count meaning the most recognizable change. However, this may only be true for a light source positioned directly above the camera and test media as was the case in the vessel. A promising aspect about this damage at angles test is the fact that the CCD camera and software had no problem recognizing the refractory damage at any angle.

LOW LIGHT CAPABILITY

The CCD camera and software recognize change of refractory under relatively low light conditions. The auto iris capability combined with the threshold level tuning parameter on the compare program provide a good low light capability (Figures 25 and 26 and Tables 6 and 7).

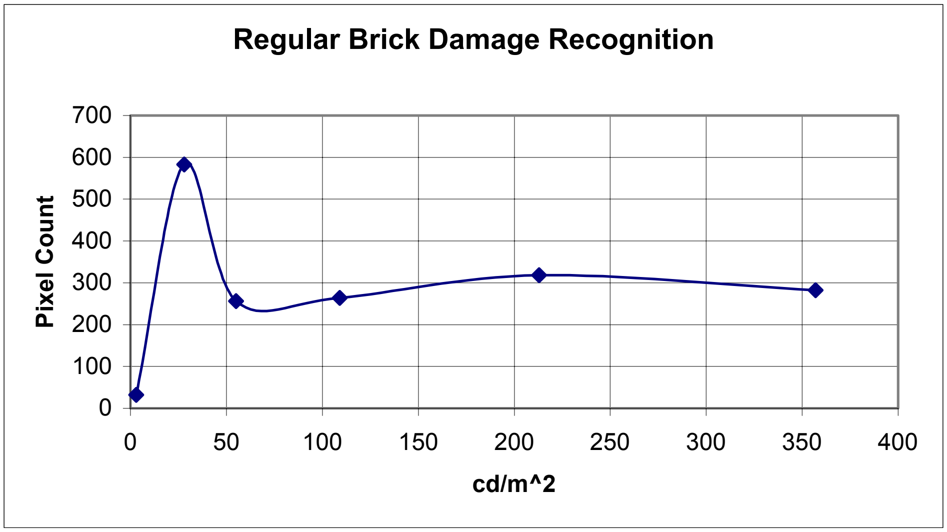

Figure 25. Regular brick damage recognition.

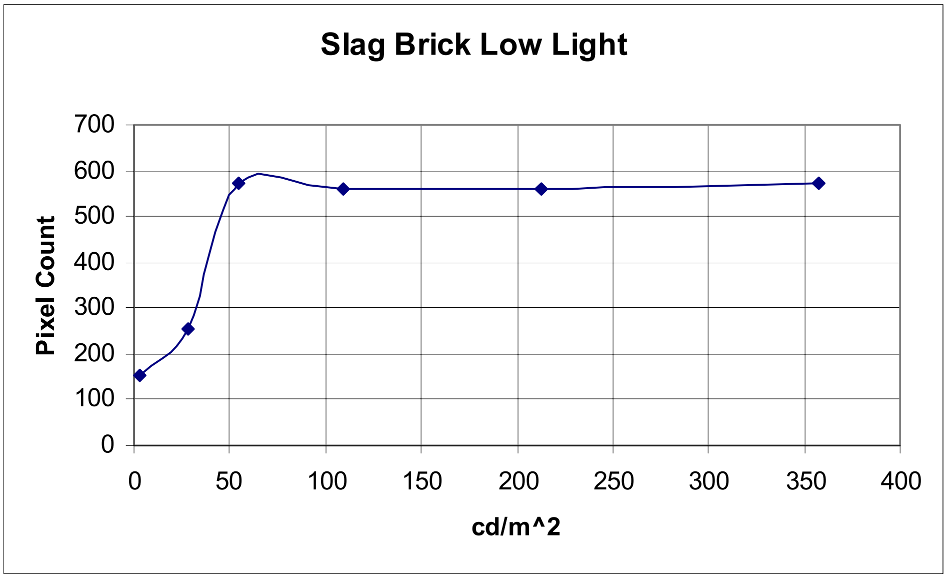

Figure 26. Slag brick damage recognition.

Table 6. Cracked brick comparison.

IMAGE 1	IMAGE 2	BLOB	PIXEL	THRESHOLD	LUM (cd/m^2)
cntr40	crck40	3	32	25	3
cntr60	crck60	3	583	40	28
cntr80	crck80	5	256	40	55
cntr100	crck100	5	264	40	109
cntr120	crck120	3	318	40	213
cnrt140	crck140	4	282	40	357

Table 7. Cracked slag brick comparison.

IMAGE 1	IMAGE 2	BLOB	PIXEL	THRESHOLD	LUM (cd/m^2)
cntr40	crck40	4	153	20	3
cntr60	crck60	9	255	50	28
cntr80	crck80	4	574	50	55
cntr100	crck100	3	560	50	109
cntr120	crck120	3	559	50	213
cnrt140	crck140	4	571	50	357

The compare program found the damage to both bricks easily with the correct tuning parameters. At the lowest light setting of 3 cd/m^2, the program required a lower threshold setting to enhance the pixel count in the damaged area. The camera could still record an image with a small crack on both a clean brick and a slag-covered brick at a luminance of 3 cd/m^2 (Figures 27 and 28).

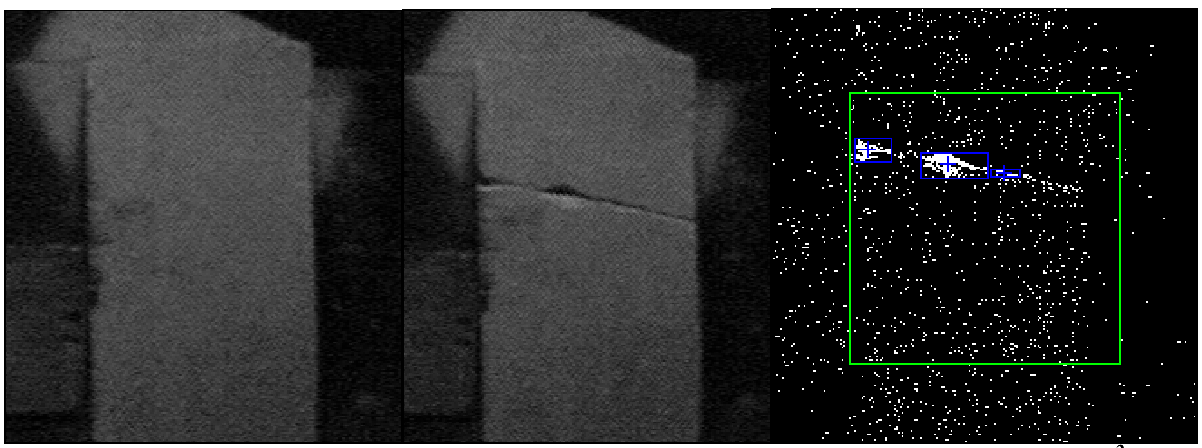

Figure 27. Undamaged brick, cracked brick, and ROI compare model (luminance of 3 cd/m^2).

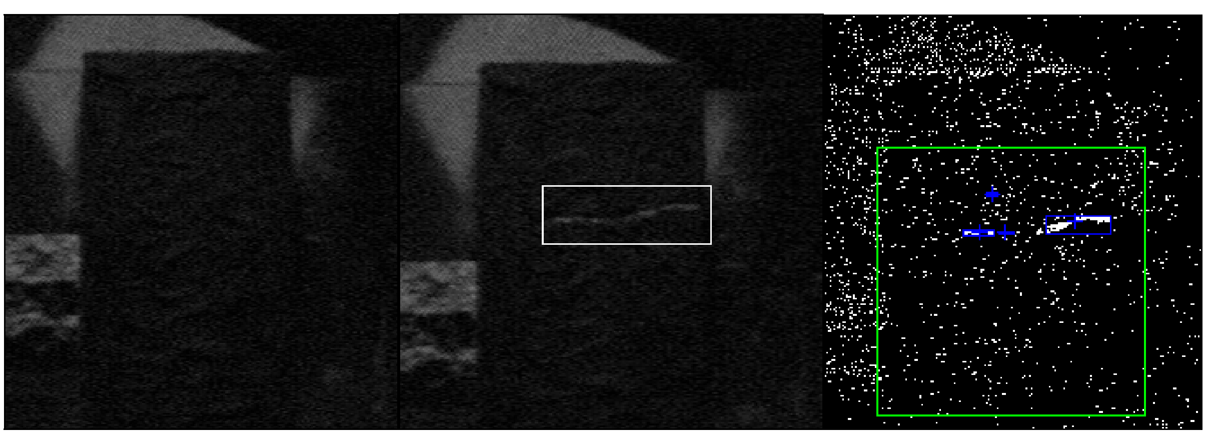

Figure 28. Undamaged slag brick, cracked slag brick, and ROI compare model (luminance of 3 cd/m^2).

INTENSE LIGHT CAPABILITY

The CCD camera fitted with the Number 2 neutral density filter produced the following change recognition imagery with an arc welder light source (Figure 29).

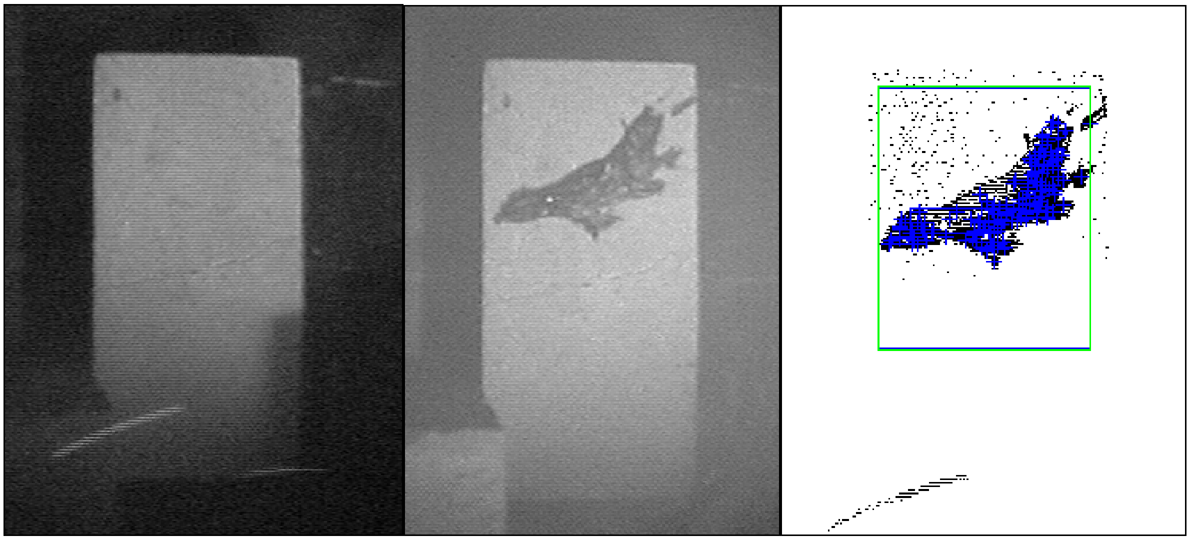

Figure 29. Undamaged brick, brick with flaw, pixel count = 621.

With the ROI compare mode (Min Size = 0; Max Size = 10,000; Threshold Level = 20), the software had no trouble recognizing this obvious change under intense light. However, when looking at just a small crack in the brick, the compare program had difficulty recognizing the crack as an image change (Figure 30).

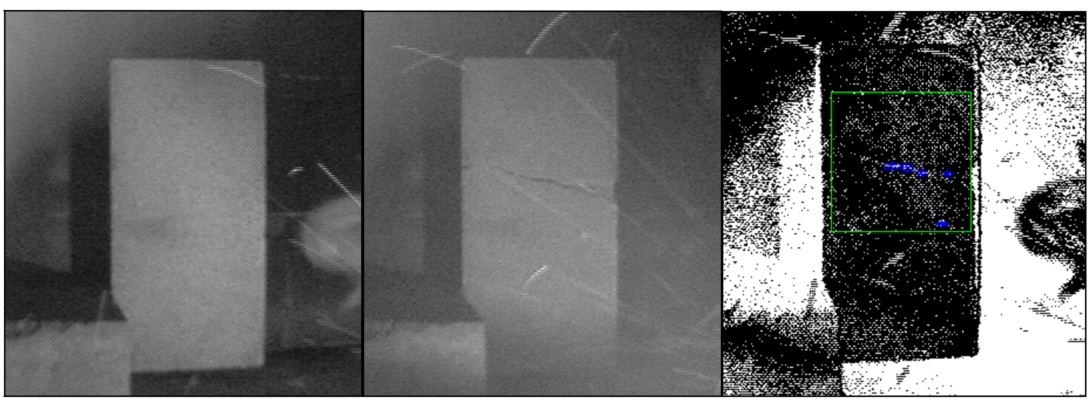

Figure 30. Undamaged brick, cracked brick, ROI compare model (pixel count = 83).

A combination of the intense light and the dark filter probably caused the crack in the brick to fade out more easily. Depending on the type and severity of flaw that must be detected, the camera and software still can monitor change in the refractory.

COMBUSTION LIGHT SOURCE

With an oxy acetylene torch as a light source, the camera and frame grabber recorded images of the firebrick looking for change. The fact that a combustion type of light is unsteady, or flickering, could cause enough instability in the image to trigger pixel change. The compare program processed the following images under the combustion light source (Figure 31).

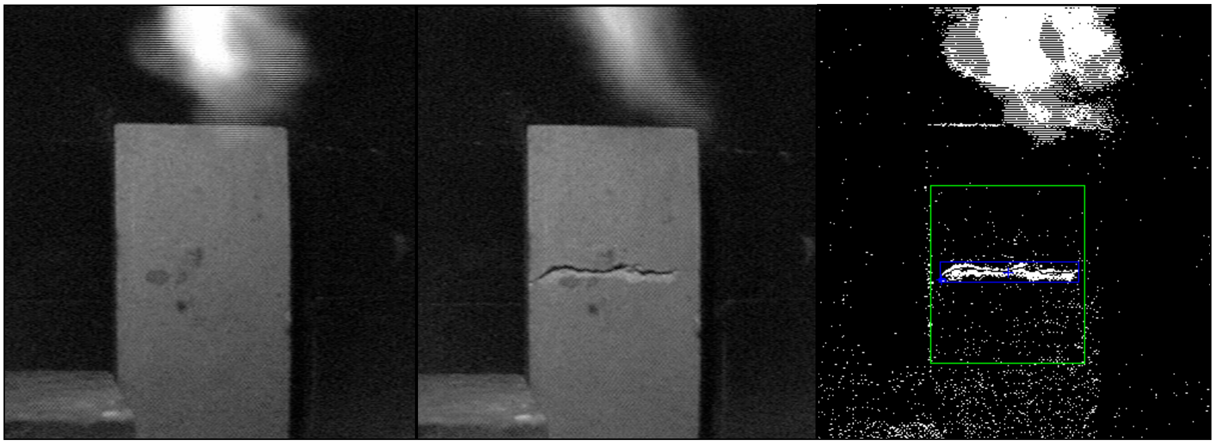

Figure 31. Undamaged brick, cracked brick, and ROI compare model (pixel count = 748).

The ROI compare program picked up the image change nicely with Min Size = 10; Max Size = 10,000; and Threshold Level = 30. Some noticeable pixel change occurred in the camera field of view, but are easily neglected using tuning parameters and the ROI frame. This oxy acetylene light source may not have fluctuated enough to represent a true combustion sort of atmosphere. If the light fluctuation in the chamber were more drastic, causing pixel change, the constant feed type of recording described in the Streaming Image Mode section using an average image could overcome this obstacle.

HOT SPOT RECOGNITION

This test run simply demonstrated that the compare program could recognize an area in the refractory that is heated to the point of glowing, dull red. The main difference with the glowing red area compared to the previous conditions was that the surface of the brick did not change by removing or adding surface area material. The following images show that the compare program easily recognizes this color change caused by concentrated heat in one area (Figure 32).

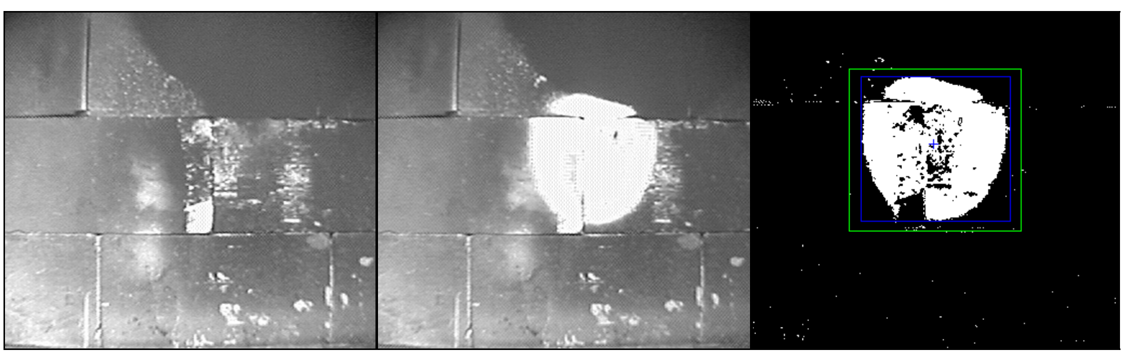

Figure 32. Refractory wall, hot spot, and ROI compare model (pixel count = 12,019).

The compare program (Min Size = 10; Max Size = 100,000; Threshold Level = 50) clearly finds the pixel change created by the hot spot. However, as the spot cooled, there was enough color change to the affected area that the spot remained on the refractory brick. Perhaps this remaining spot does not pose any problems, but there may be instances where it could. The main objective was to recognize an area in the refractory that glowed due to excessive heat.

STREAMING IMAGE MODE

This test uses a series of live images at a frequency of four images or cycles per second. MSE engineers modified the code within the compare program to capture a base image and then view a series of images comparing each one to the base image. The software averages the changes registered as a pixel count over the entire series eliminating data spikes that may occur from temporary interference. This test run contains three main categories designated: 1) temporary interference; 2) permanent change; and 3) slow-growth change. The temporary interference (Figure 33) consisted of waving a black 2 X 4 in front of the camera for approximately 1 s.

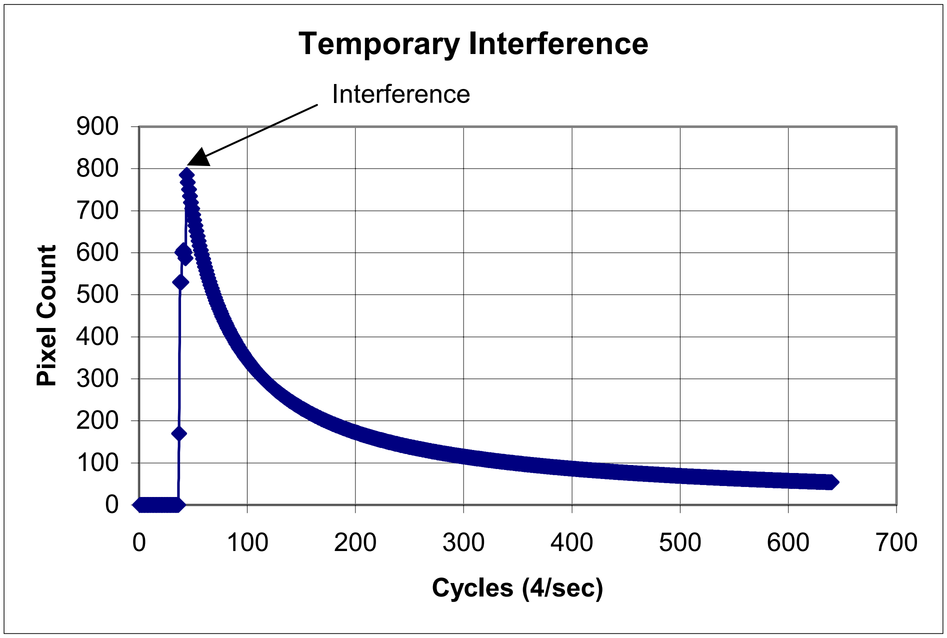

Figure 33. Temporary interference.

The frame grabber recorded the interference blob at approximately 800 pixels and as the cycles increased for a total of 640 or 3 min., the average value decayed toward zero.

The permanent change test included the same 2 X 4, but this time the interference remained against the wall simulating a permanent change (Figure 34).

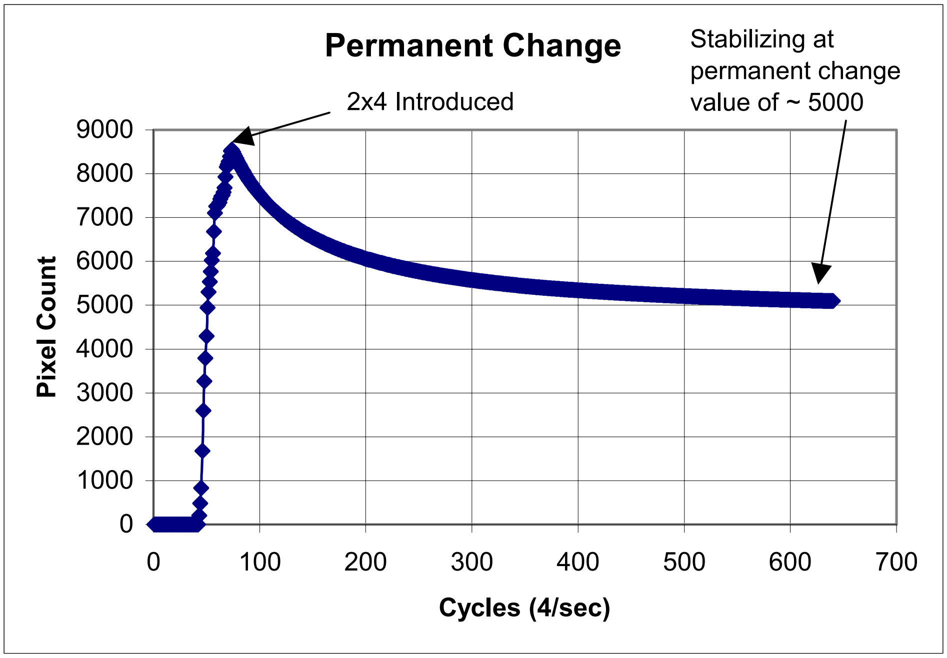

Figure 34. Permanent change.

The regular compare program used the base image and last image of the cycle for image change recognition (Figure 35).

Figure 35. Base image, last image, and image change recognition.

The last portion of the streaming image test looked at how the compare program would recognize a slow growing change (Figure 36) similar to erosion in refractory. The base image received two sprays of paint at different times simulating erosion.

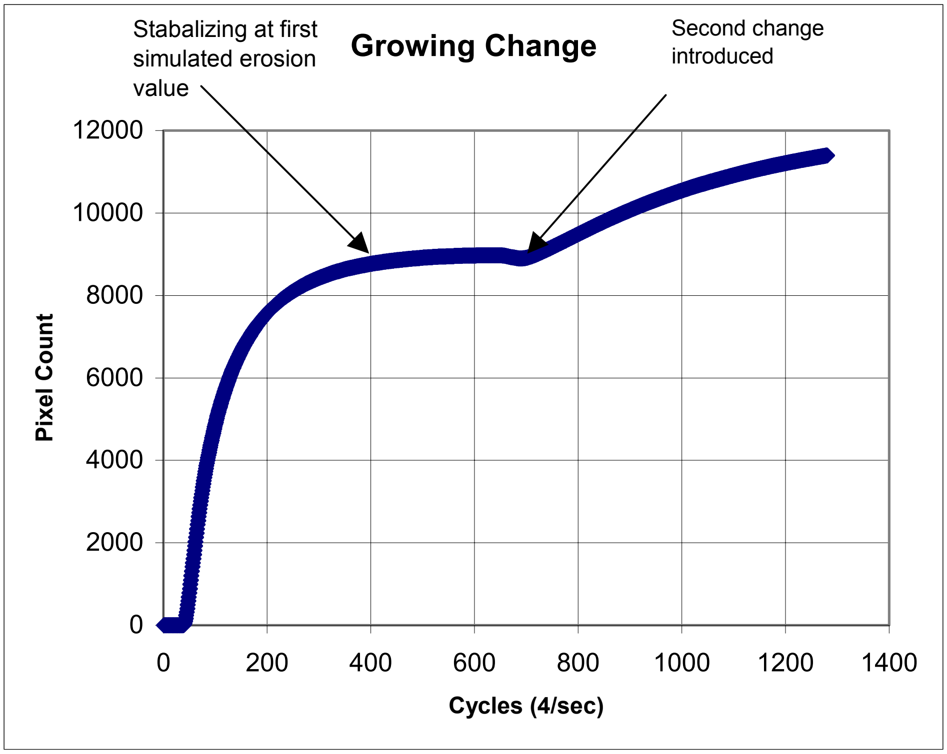

Figure 36. Growing change.

This run lasted 1,240 cycles or 6 min. and averaged values the entire time until stabilized.

CONCLUSION

The goal of this test project was to demonstrate the capabilities and discover the limitations of the high-temperature pinhole camera mated to the frame grabber and compare software. While these tests may not have accurately simulated conditions that may be encountered inside a gasification chamber, they did show how versatile, accurate, and reliable this on-line refractory confirmation system can be. The eight different test categories included below demonstrated some important capabilities of the camera and software. However, this software is not limited to the tests performed in this project and may be tailored to evaluate images in other ways.

TAPE TEST

This test was important in establishing a quantitative check of the pixel count and verifying pixel change recognition from black to white or white to black. The test proved that the pixel count is directly proportional to the area changed in the image comparison. Future applications may include turning the pixel count into measurable dimensions. This dimension would also trigger an alarm to the operator if the area exceeded a certain size.

The compare program also recorded pixel change no matter what end of the gray scale (0 to 255) they originated from. The gray scale or threshold level could play a role in distinguishing between types of changes that occur to the refractory. For example, slag or slag deposits on the refractory would be a generally darker change than a crack. The difference in the pixel gray level could enable the compare program to distinguish between these types of changes.

ANGLE REPEATABILITY

This portion of the test simply proved that very little error was attributed to repositioning of the firebricks. If a mechanical device pivoted the camera to view more of the gasification chamber refractory, it would be important to stop the camera in a fairly precise and repeatable position each time before recording images.

DAMAGE RECOGNITION AT ANGLES

The camera and software can recognize refractory damage from many different angles. This ability relies on many variables, such as lighting, refractory surface, and distance. This test section employed the ROI capability of the compare program allowing the software to look only at a particular region within the entire field of view. This could be a particularly useful attribute for neglecting areas in the gasification chamber that change rapidly and drastically throwing off the compare program. The compare program can zero in on an area of interest.

For future applications, the ROI could shift to predesignated coordinates established in the field of view. The coordinates would exist in the compare program code telling the compare program to view the ROI for a certain number of cycles, which converts to time. The ROI could then shift to the next coordinate until the desired areas are covered and then repeat the cycle. This method could cover just portions of the entire field of view or the whole field like a grid. A window interface would control the cycle time and desired coordinates. The camera could focus on different regions of the refractory wall without moving physically.

LOW LIGHT CAPABILITY

The camera and frame grabber software can detect refractory damage under extreme low light conditions. The camera auto iris capability combined with the threshold level tuning in the compare program allow for recognizing refractory damage in light luminance down to at least 3 cd/m^2. This could possibly be a valuable capability inside certain regions of the gasification chamber that may be poorly lit.

INTENSE LIGHT CAPABILITY

Using neutral density filters in the camera housing, the camera and frame grabber can withstand extreme light and still find change in the refractory. Again, depending on the conditions within the gasification chamber, this could be an important aspect. The filters come in different shades to match light intensity. Further testing could explore the use of different types of filters, not neutral density, but filters that may enhance the image and bring out certain types of refractory degradation. For example, depending on the light source, a polarized filter may remove glare and sharpen an image for change recognition.

COMBUSTION LIGHT SOURCE

This test run simulated conditions that may be encountered in an incinerator or gasification chamber. In this case, the oxy acetylene flame did not produce enough light fluctuation to hinder the compare program. However, if the light from a flame in a gasification chamber was not as steady, the flickering light could produce false results in the compare program. Some programming modifications would eliminate this potential problem. The frequency or frame grabber image capture cycle can cover a large range of time intervals. A particular cycle time could eliminate the false image change. The software also has the ability to compile a series of images and average the pixel count for the entire series. This method could also eliminate light fluctuation problems by averaging the pixel change over a long series of images. The section titled Streaming Image Mode explains the advantages of this method in more detail.

HOT SPOT RECOGNITION

Concentrated heat in one area (hot spot) of the refractory could pose a hazard to the integrity of the gasification chamber wall. When this hot spot occurs, the refractory undergoes a color change that is easily picked up by the pinhole camera and the frame grabber. For future testing, it may be interesting to use an infrared camera as a primary image sender. The frame grabber is capable of recording any type of image and the compare program converts the image into gray contrast pixels regardless of the source. The infrared camera could be valuable for detecting temperature changes in certain areas of the gasification chamber.

STREAMING IMAGE MODE

The streaming image mode with the running average is probably the most applicable and useful method of monitoring refractory. This allows frequent monitoring of the refractory with data acquisition. The running average negates high-magnitude change by eventually stabilizing to the real change value. The cycle frequency is capable of recording images at any time interval with the ability to send data to a separate file for statistical plotting. The program could also extract images from selected cycles for comparison on a regular basis. Since a large concern in a gasifier is the erosion of the refractory, what was demonstrated here in a frequency of 1/4 s. may be expanded to days and weeks.

Overall this has been a successful test by exploring the capabilities of the CCD pinhole camera coupled to the frame grabber and compare program. The camera has a high enough resolution to recognize change in the refractory under several adverse conditions. The compare program tuned with the many flexible parameters has the ability to process this image change into various pixel blobs and distinguish or isolate the significant changes from peripheral changes. This portion of the project indicates that the high-temperature camera and software system are ready for the next step of looking at actual gasification chamber refractory.

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3. Website: www.matrox.com/imaging/products/orion/home.cfm.

4. Website: ddk.zeno.com/reference/filestreamformats/array/default.html.

5. Website: www.crompton.com/wa3dsp/light/lumin.html.

6. *New Crystalline Optics*, New Jersey:Edmund Industrial Optics, 2003, p. 87.

LIST OF ACRONYMS AND ABBREVIATIONS

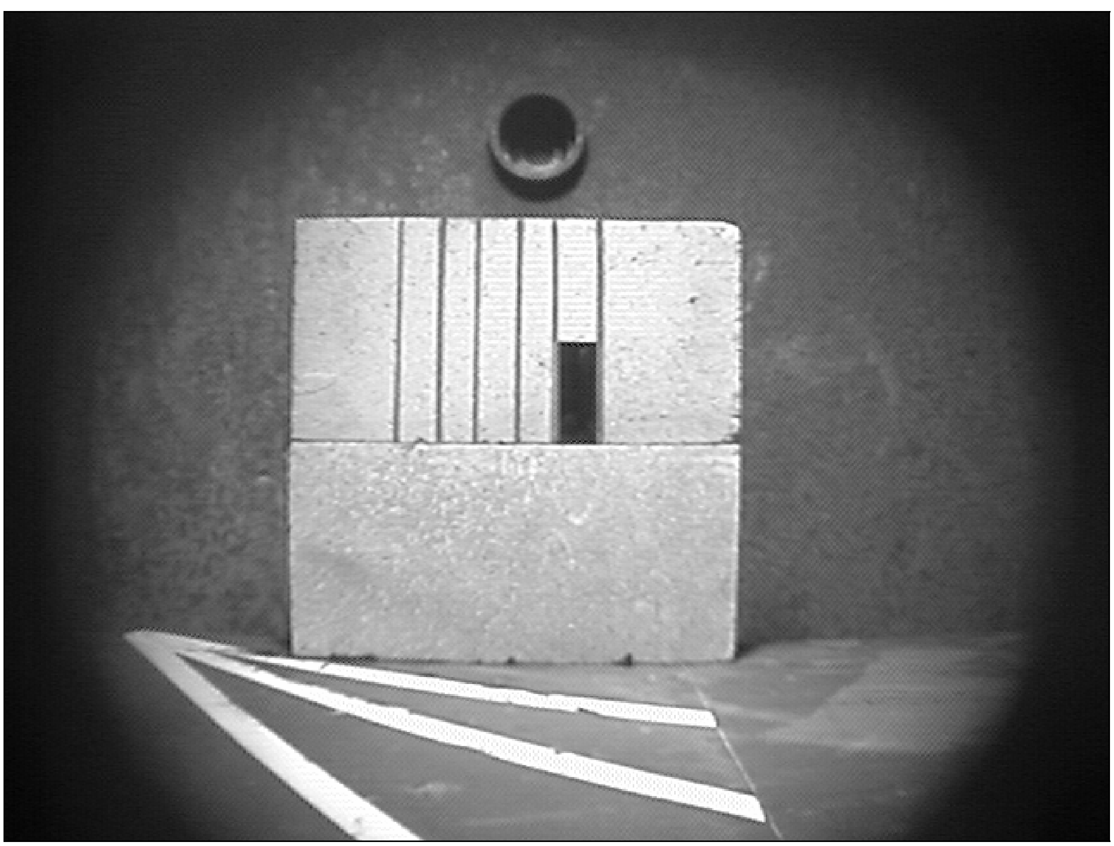
BMP	bitmap
CCD	charged-couple device
DOE	U.S. Department of Energy
MSE	MSE Technology Applications, Inc.
PC	personal computer
ROI	region of interest

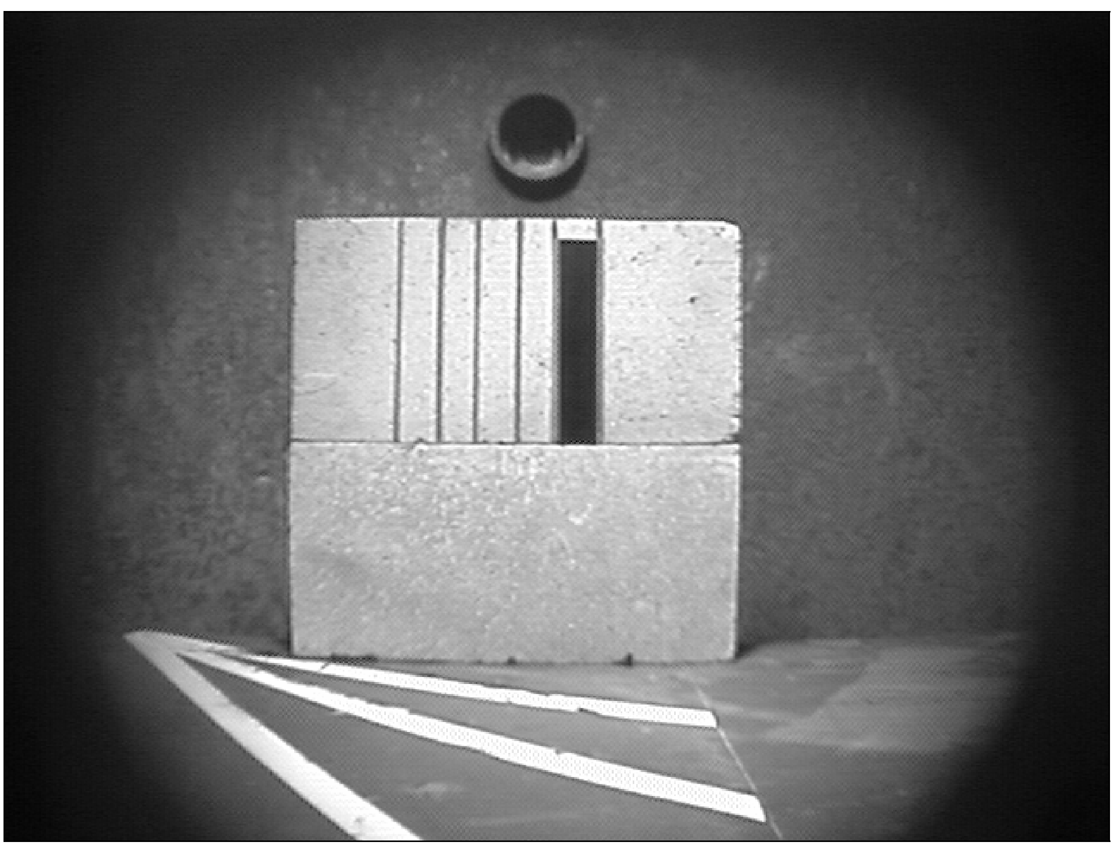
UNITS

%	percent
°C	degree(s) Celsius
B	byte(s)
cd/m^2	candela per square meter
GB	gigabyte(s)
GH	gigahertz
in.	inch(es)
m	meter(s)
m^2	square meter(s)
MB	megabyte(s)
min.	minute(s)
mm	millimeter(s)
s.	second(s)
W	watt(s)

APPENDIX A

Tape Test Images and Data





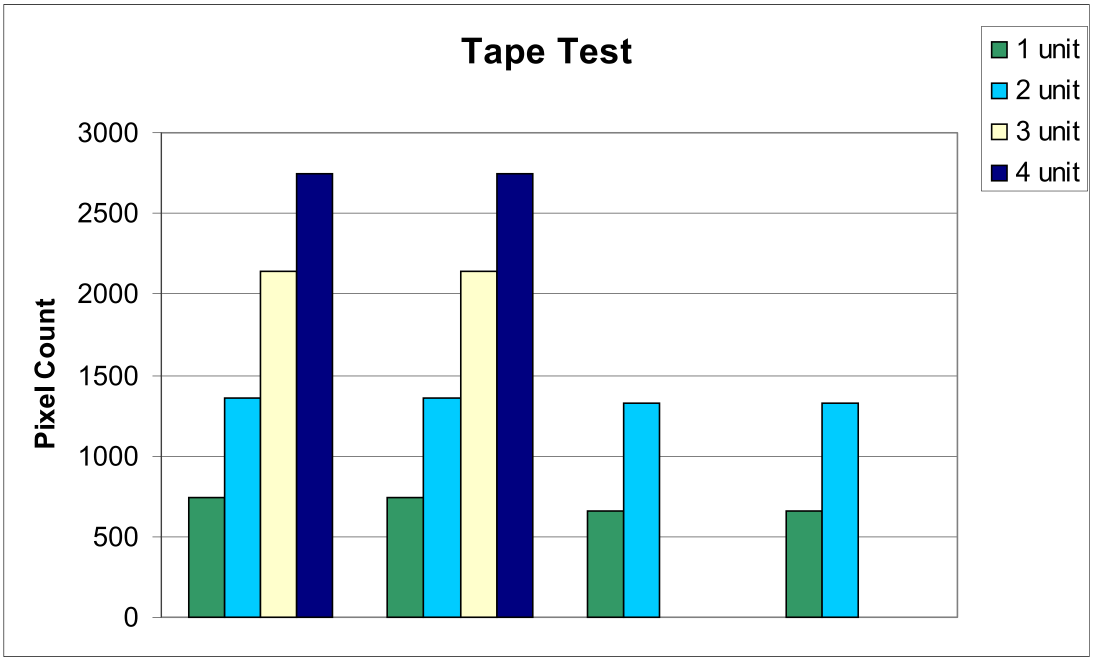
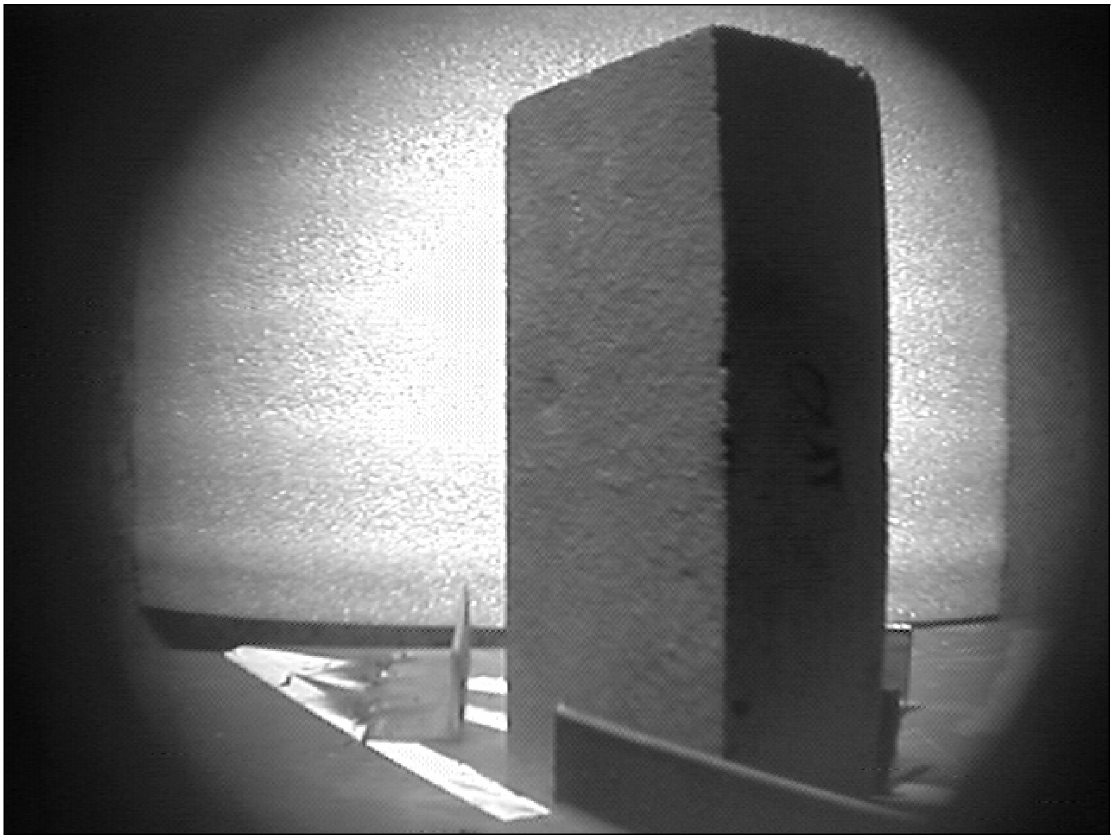
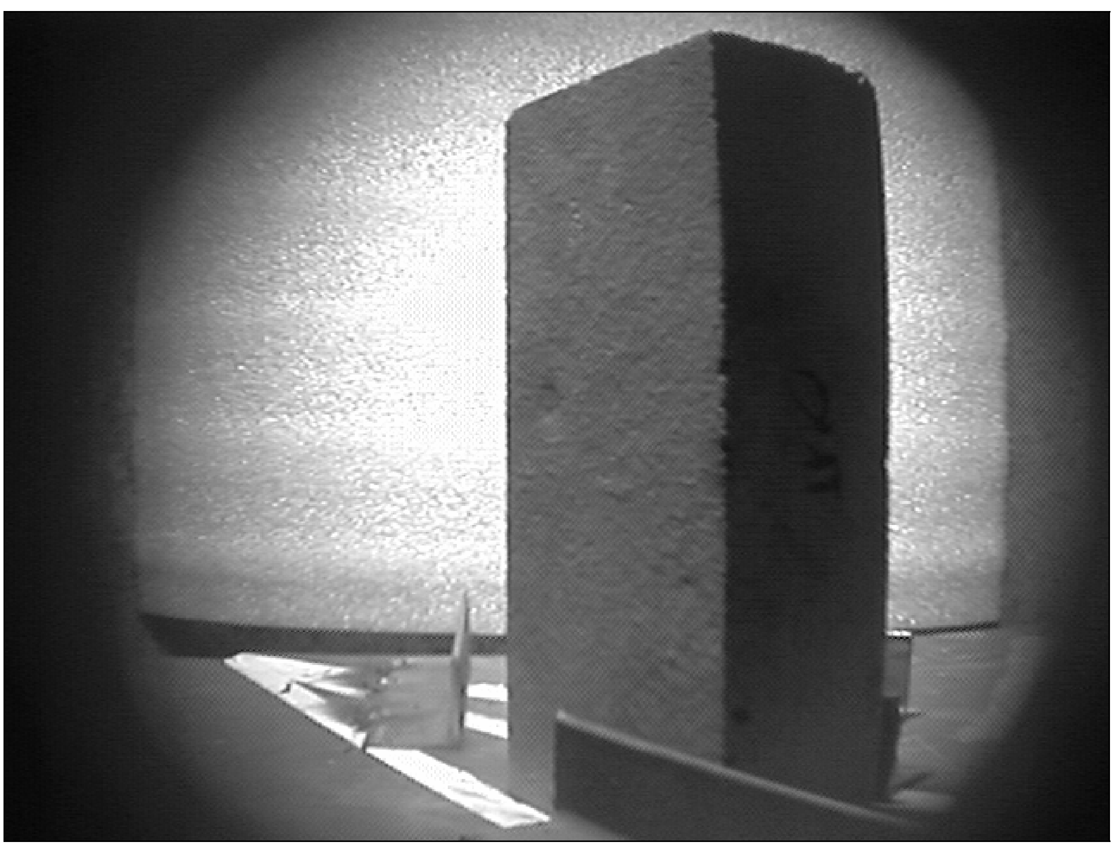


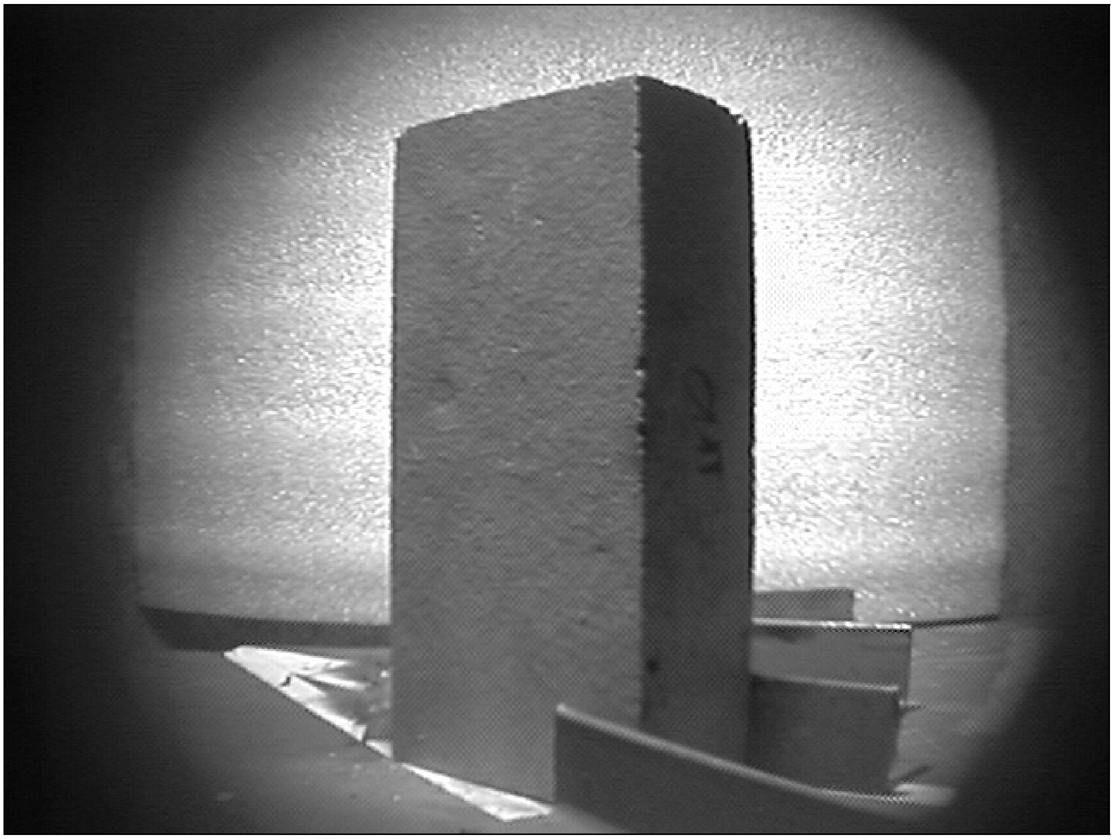
IMAGE 1	IMAGE 2	BLOB	Δ AREA	PIXEL	
0	0	1	0	0	
0	2	1	2	1356	0 --> 2
0	3	1	3	2138	
0	4	1	4	2745	
2	0	1	-2	1356	
2	2	1	0	0	
2	3	1	1	738	
2	4	1	2	1324	2 --> 4
3	0	1	-3	2138	
3	2	1	-1	738	
3	3	1	0	0	
3	4	1	1	661	
4	0	1	-4	2745	
4	2	1	-2	1324	
4	3	1	-1	661	
4	4	1	0	0	

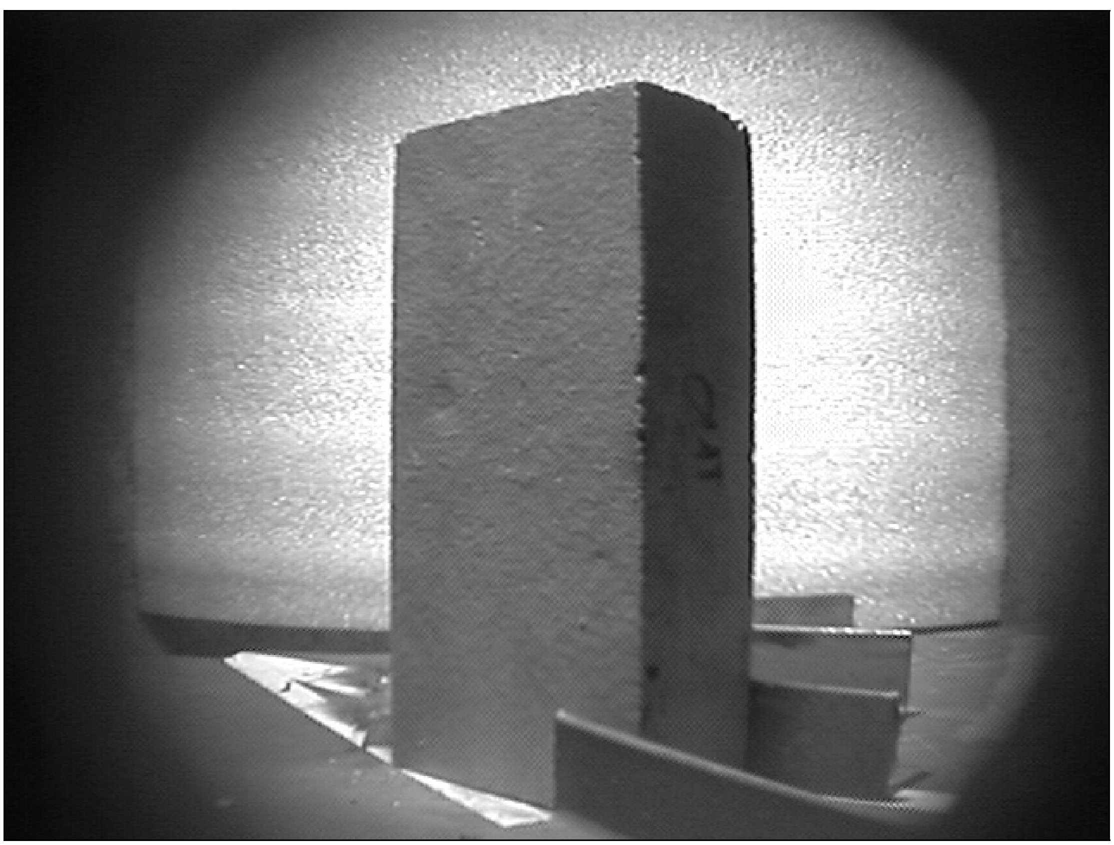
APPENDIX B

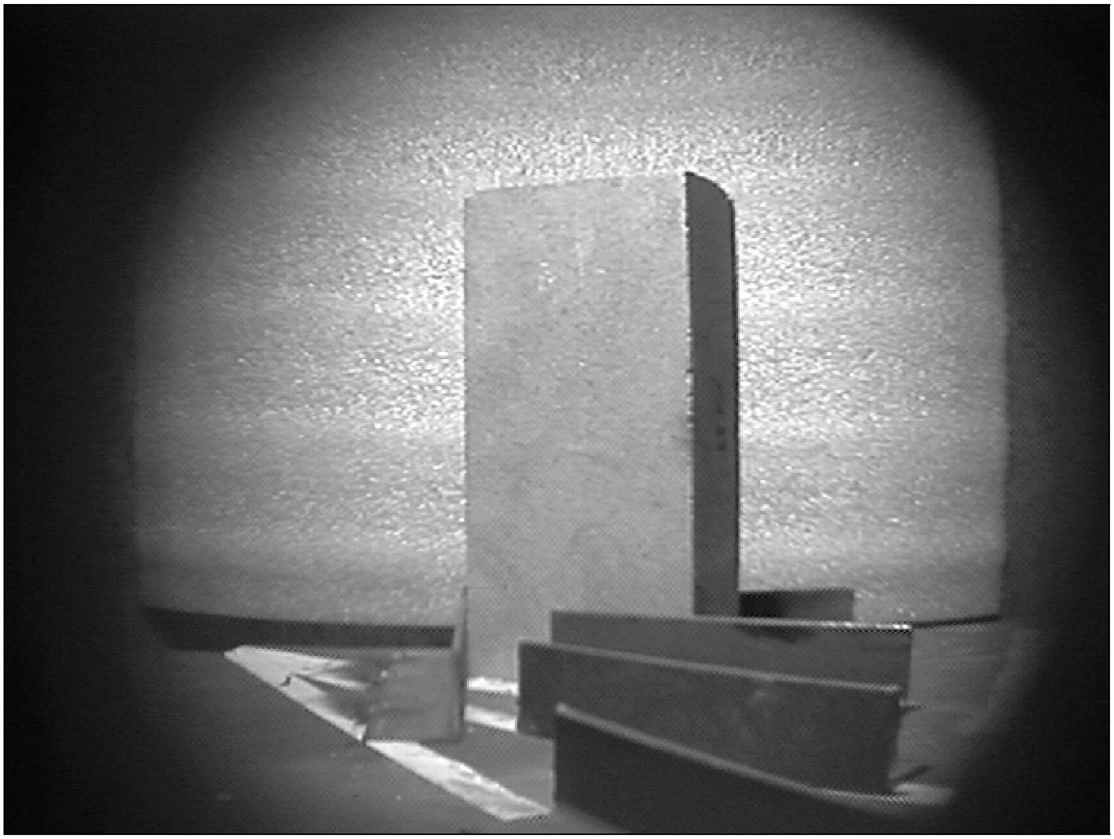
Angle Repeatability Images and Data

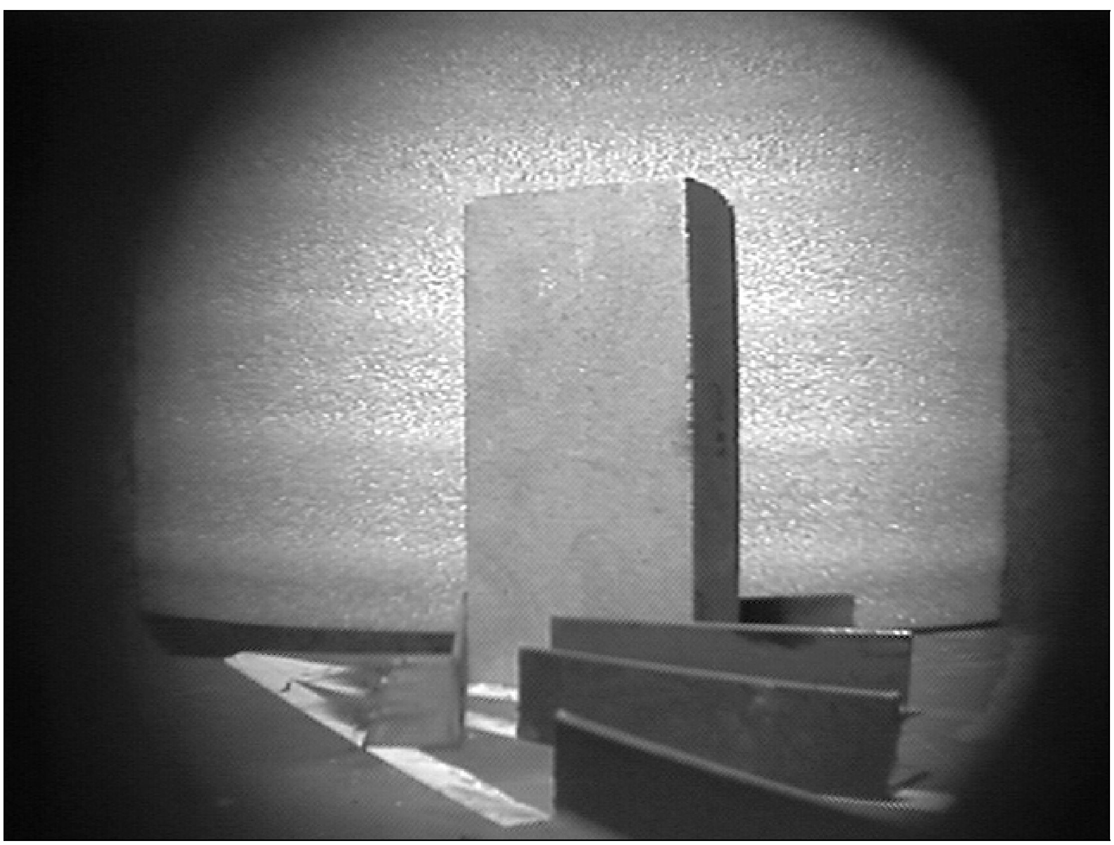


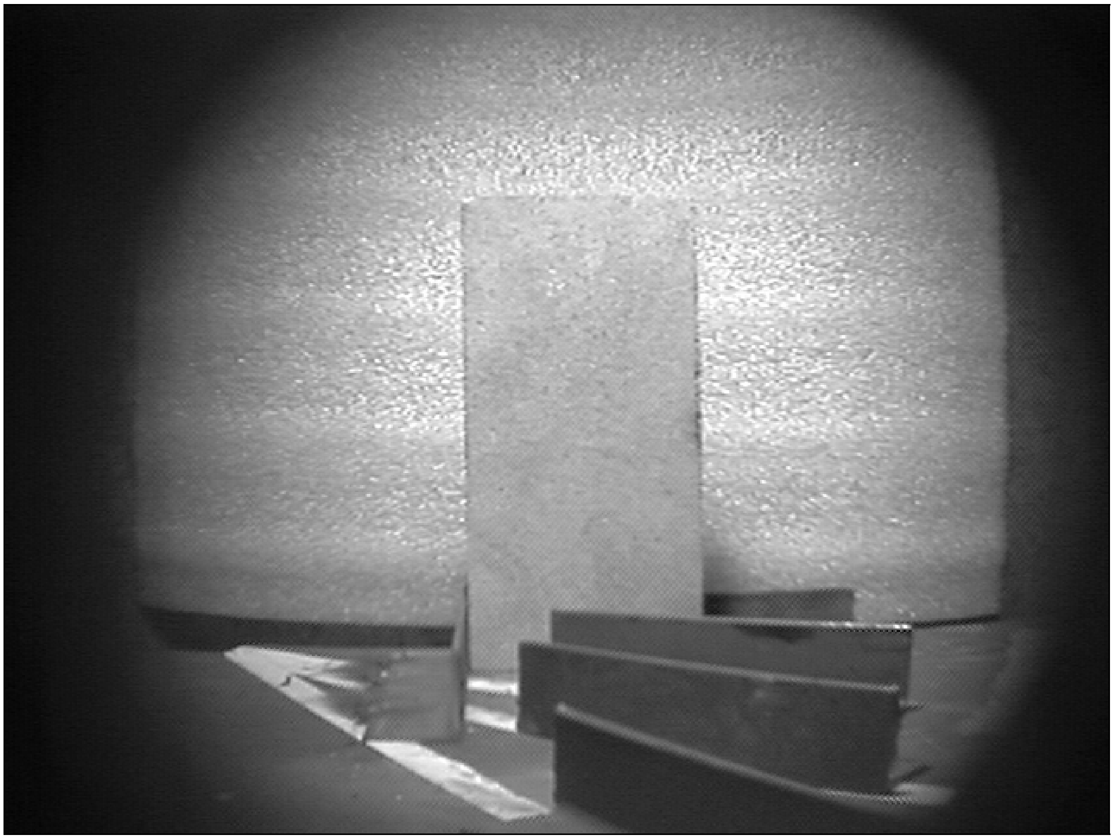












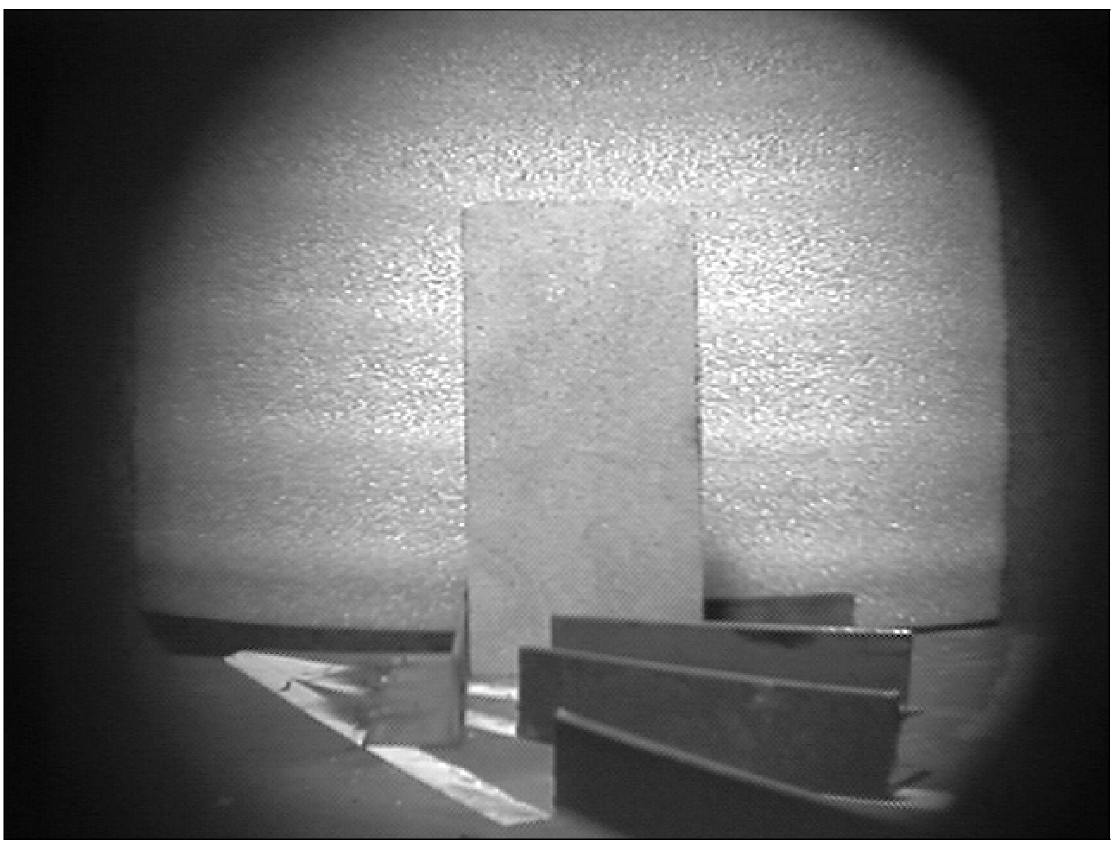
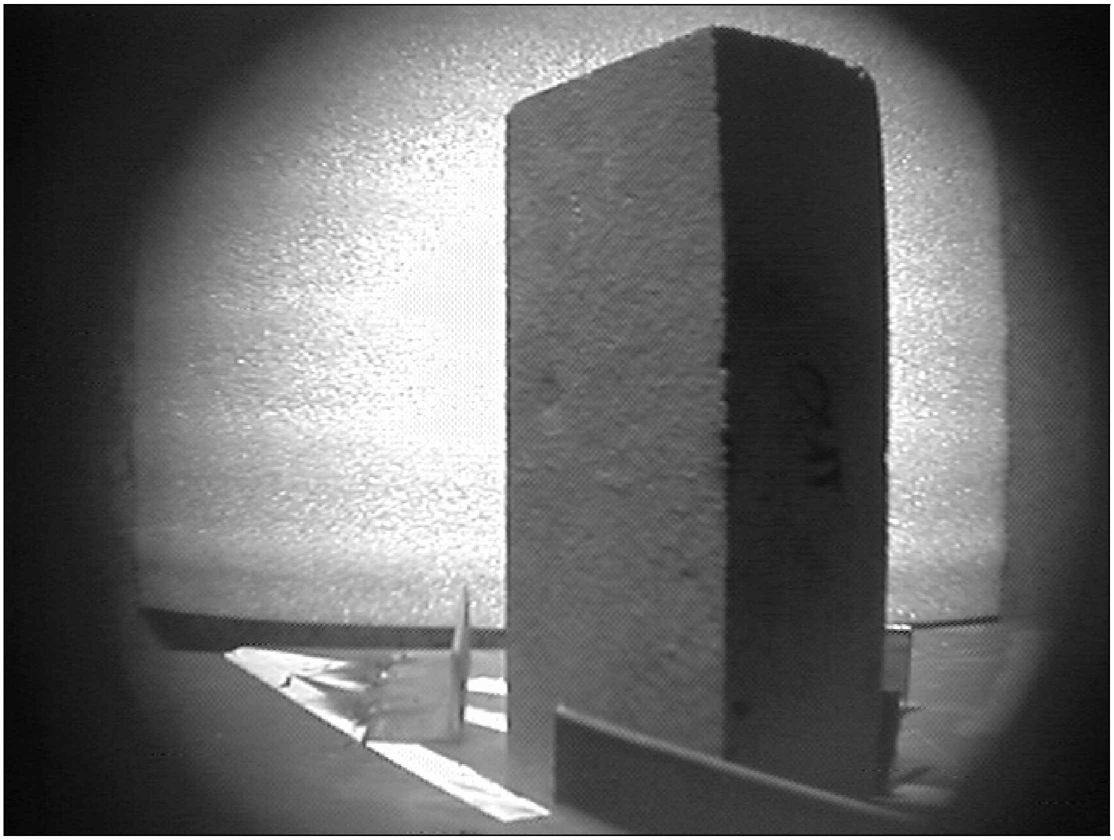
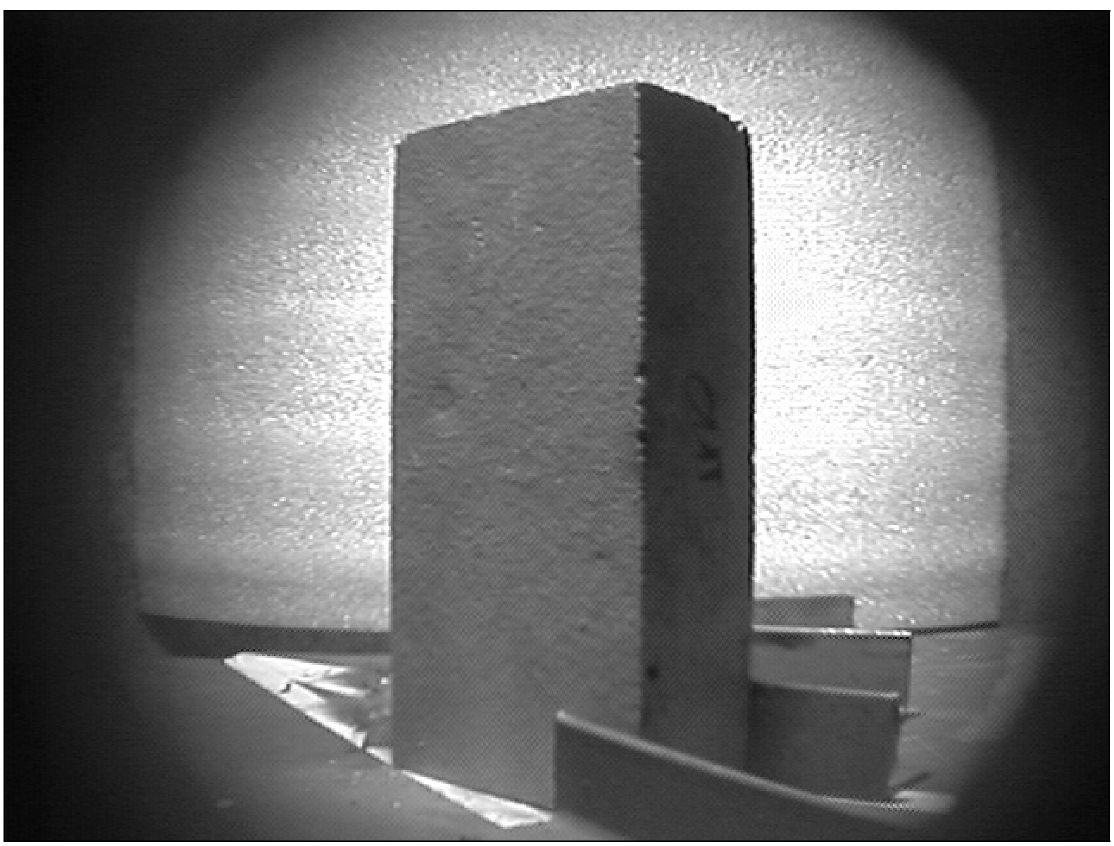


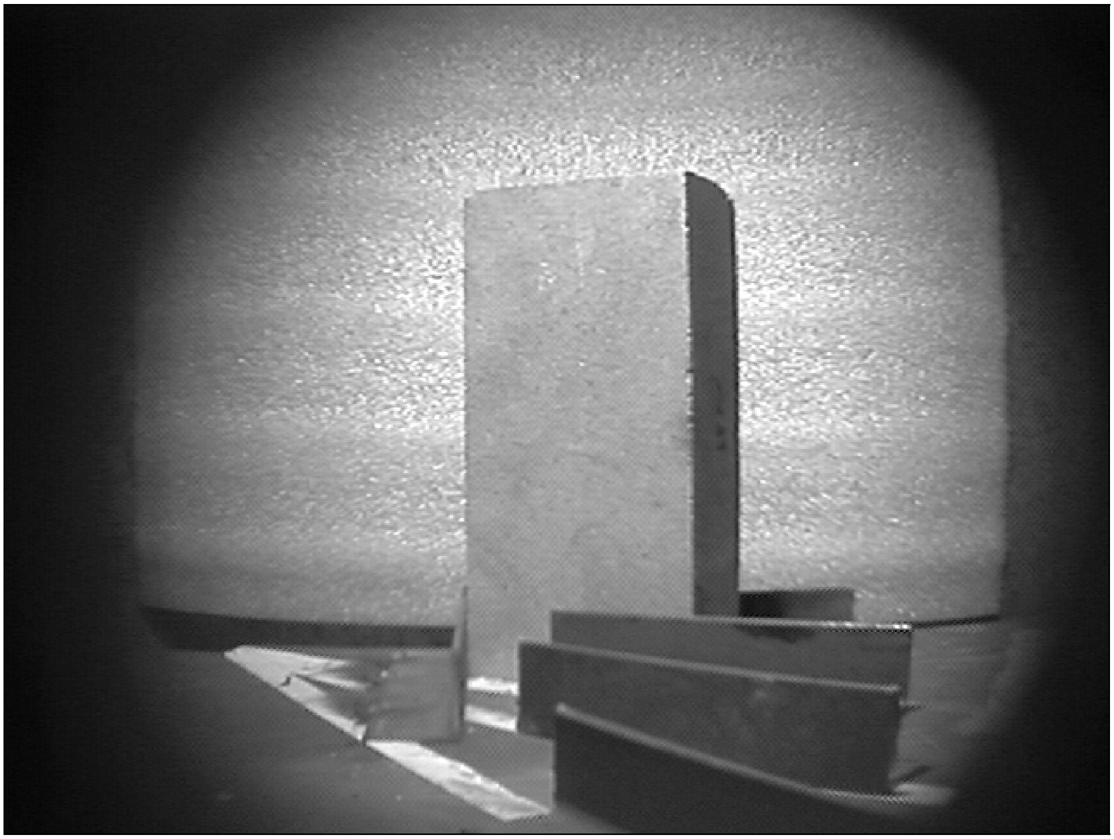
IMAGE1	IMAGE 2	BLOB	PIXEL
30A	30B	35	154
45A	45B	0	0
60A	60B	0	0
90A	90B	0	0

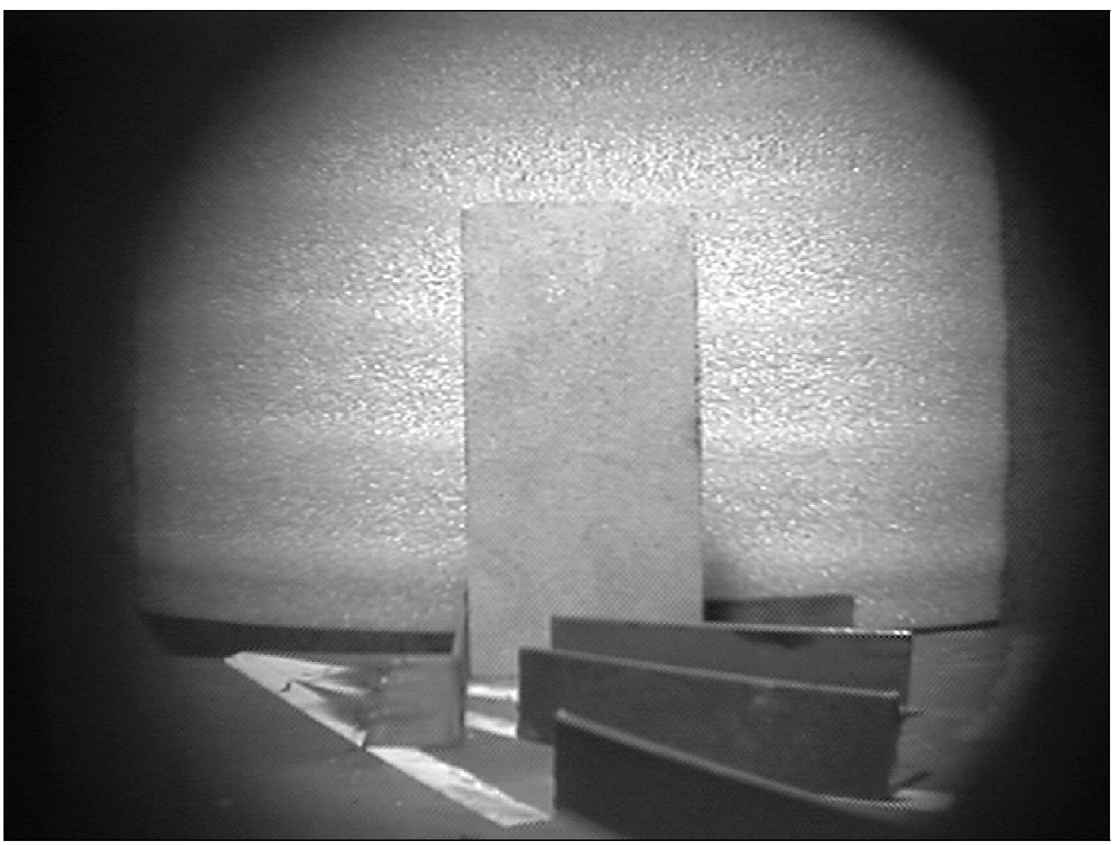
APPENDIX C

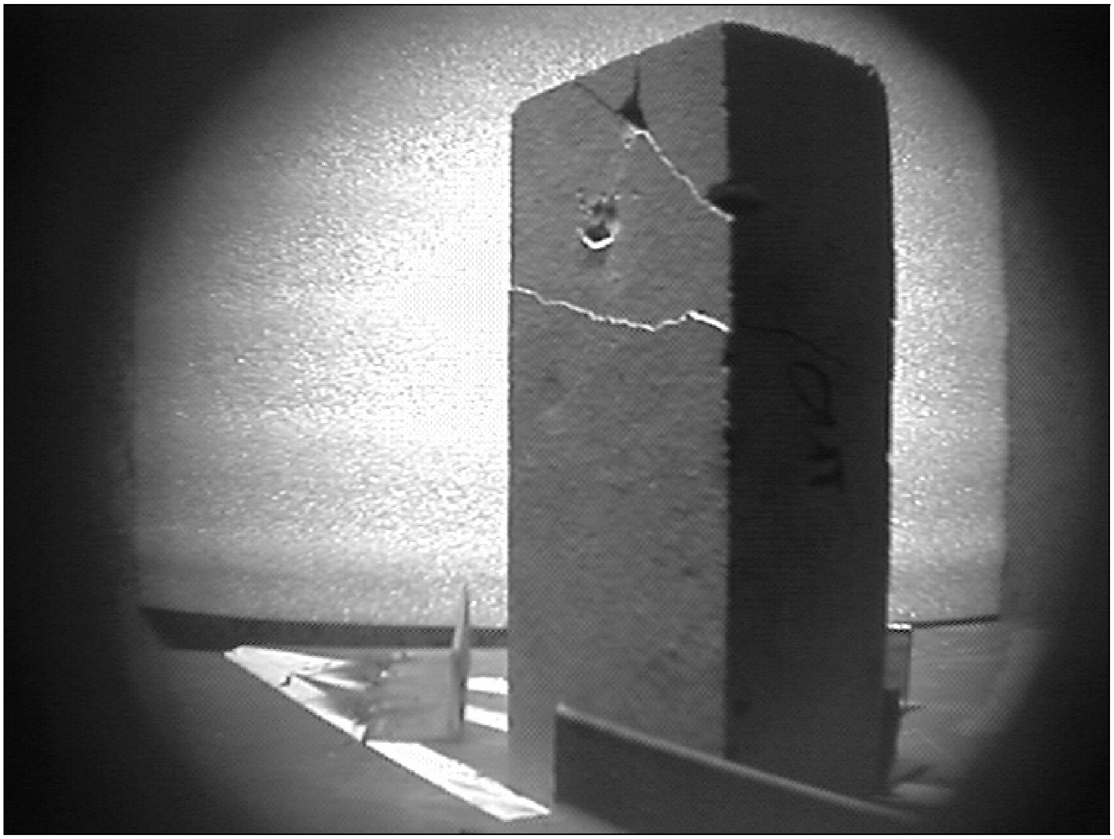
Damage Recognition at Angles Images and Data

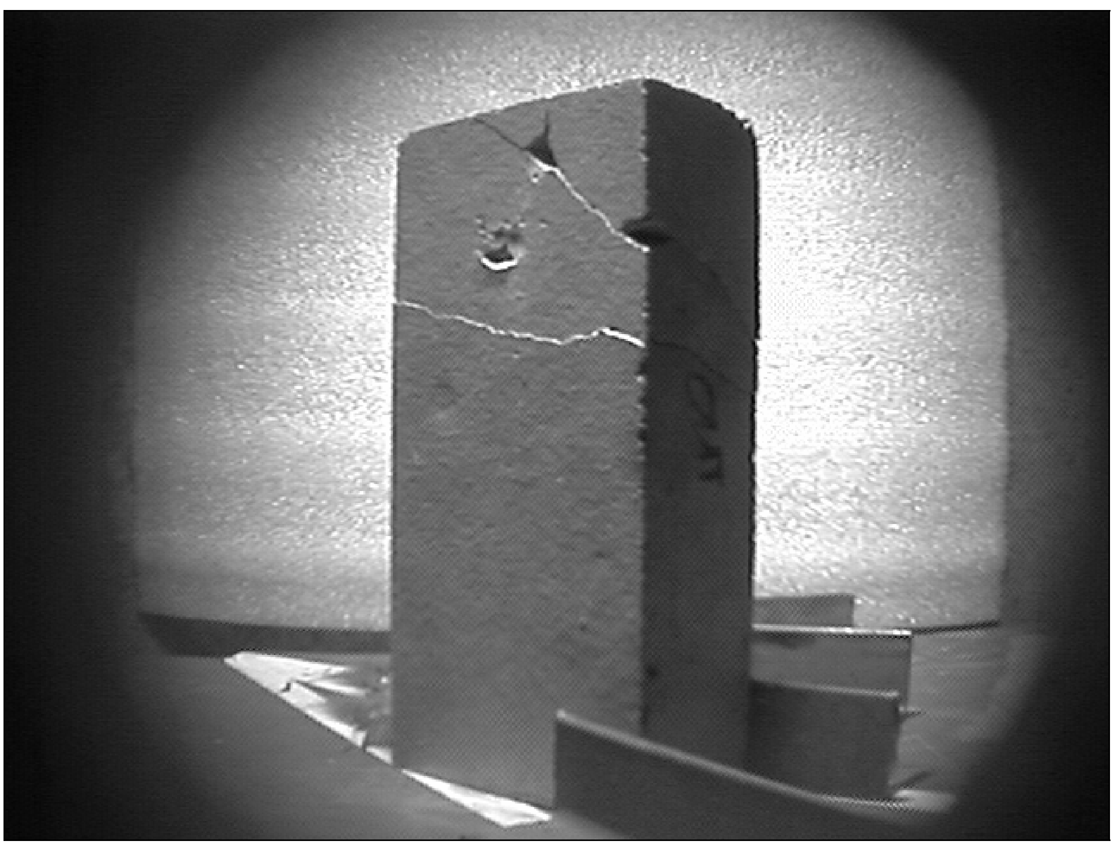


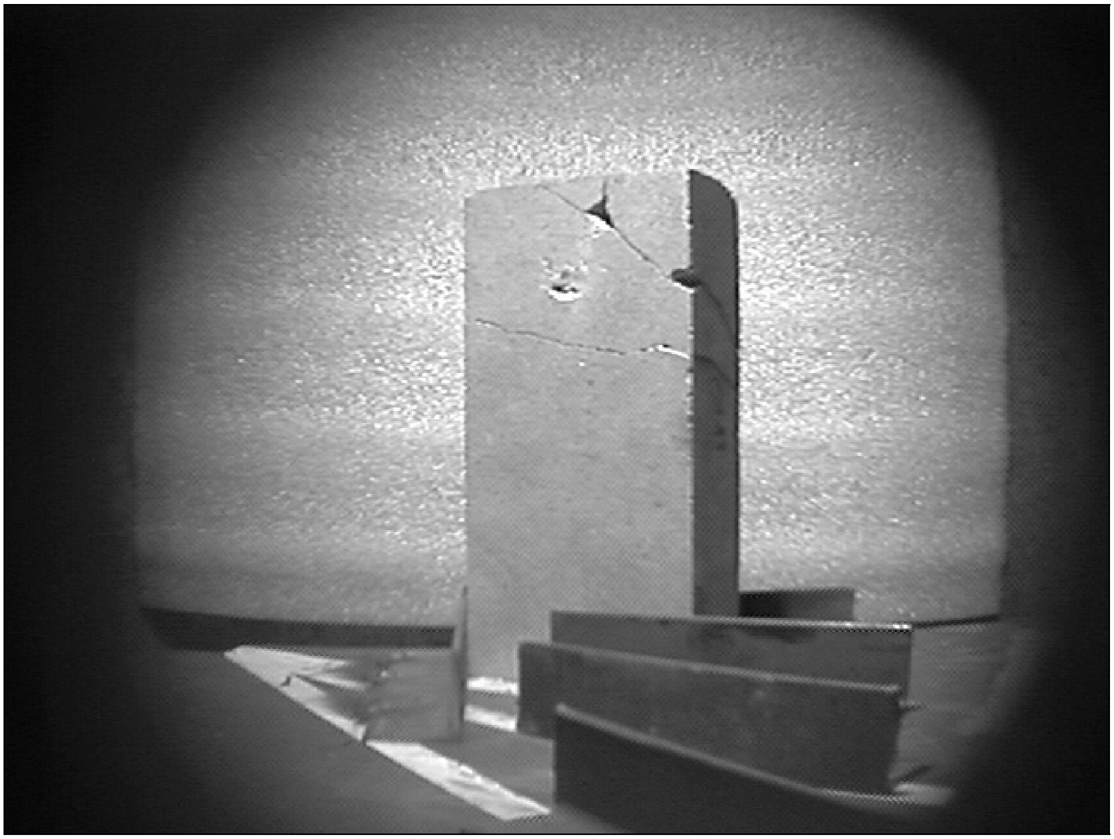


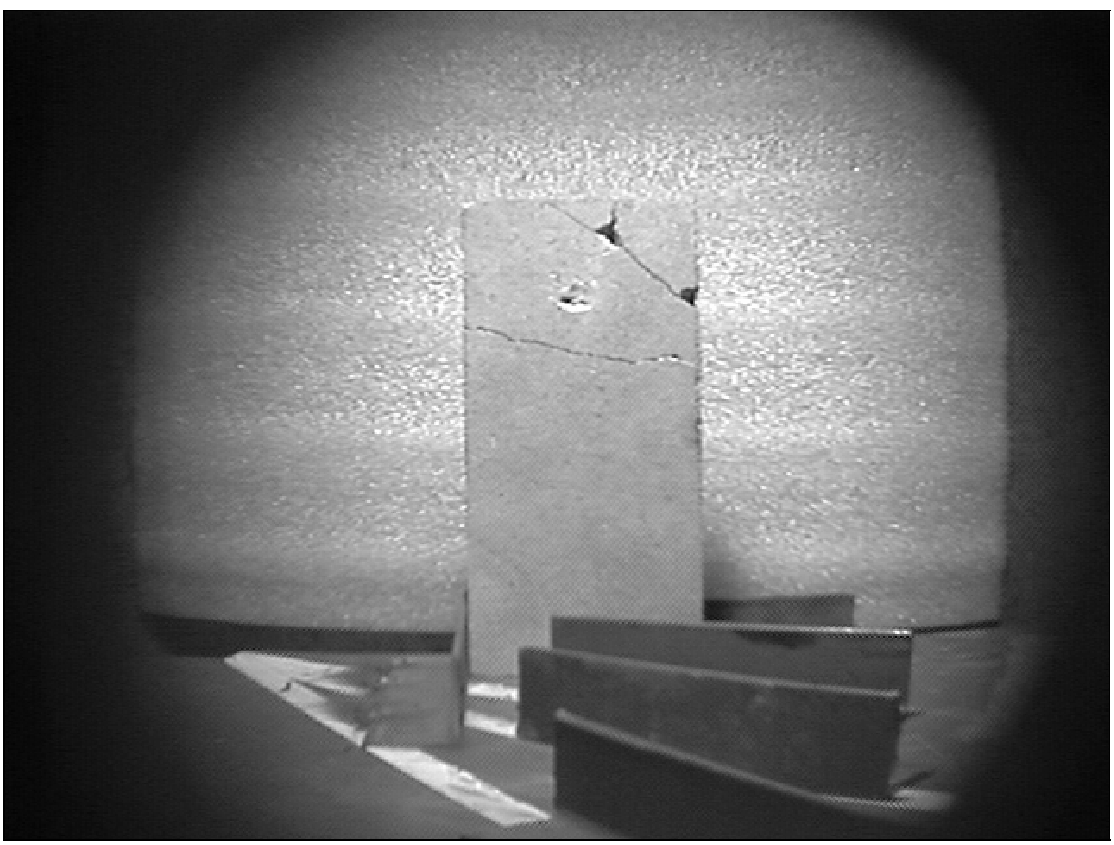






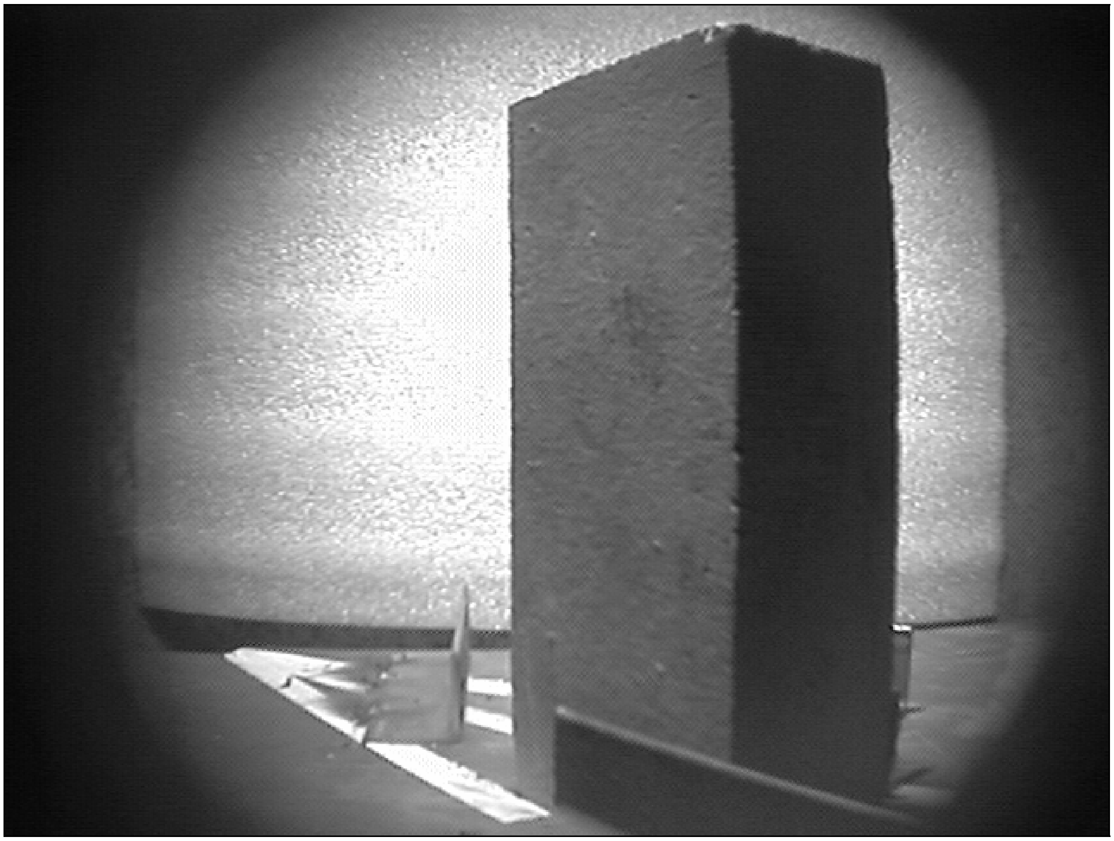


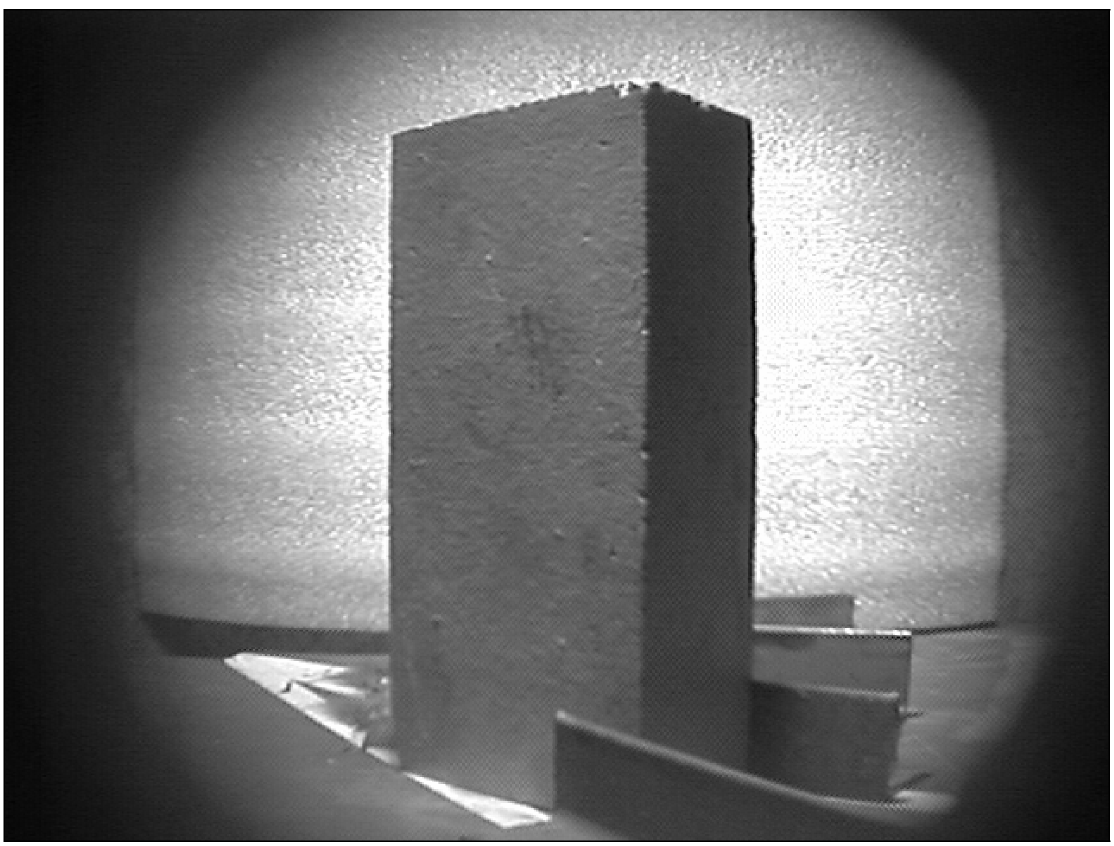


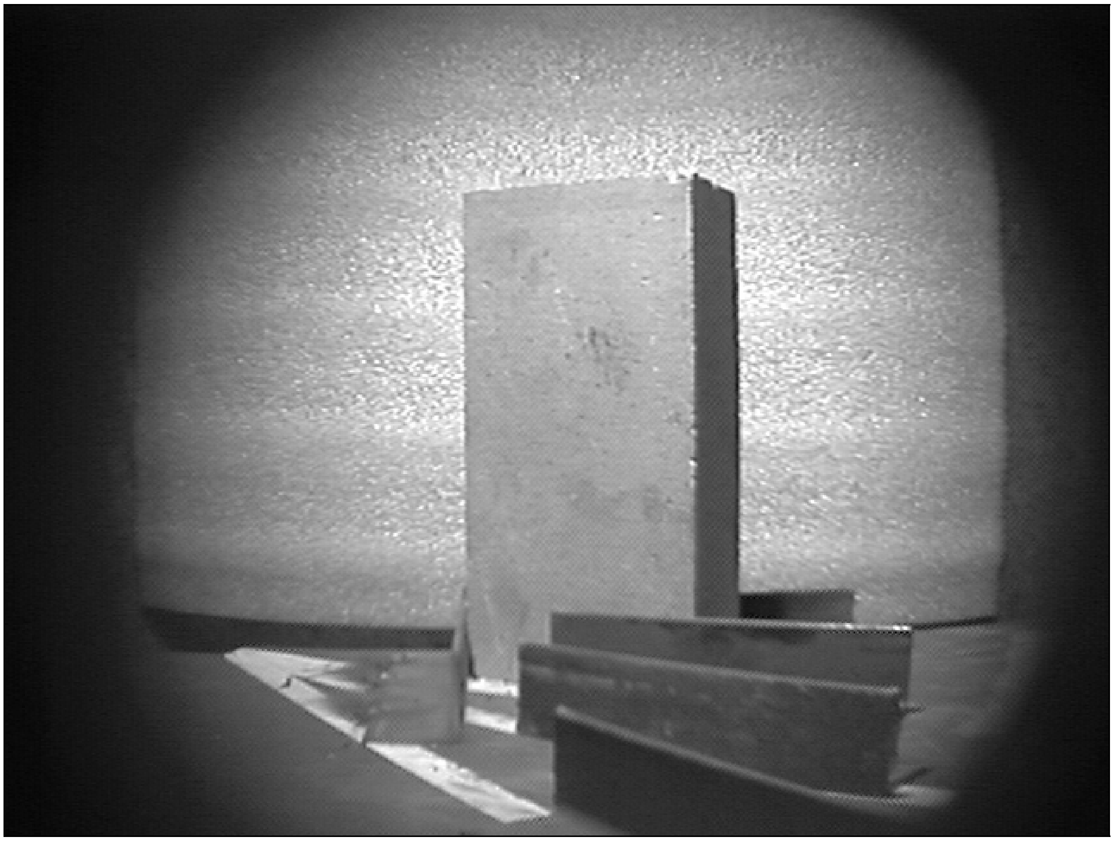


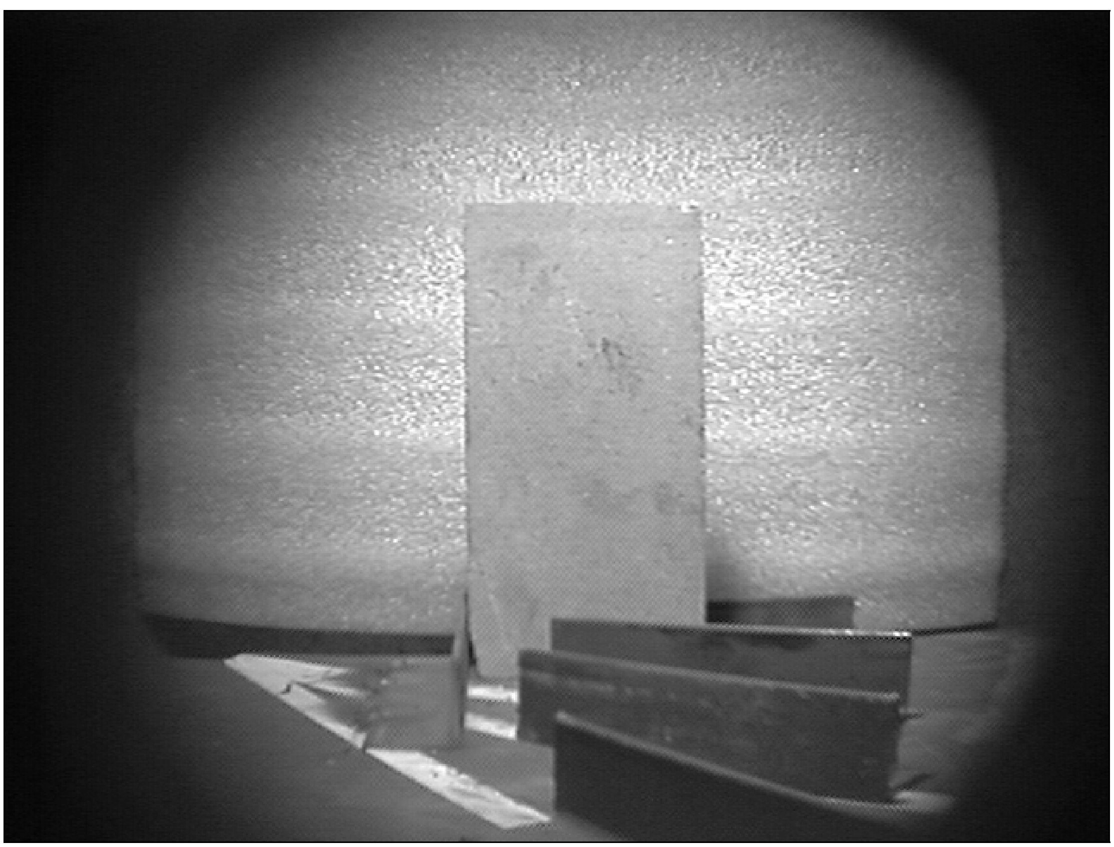
Crack Damage Run

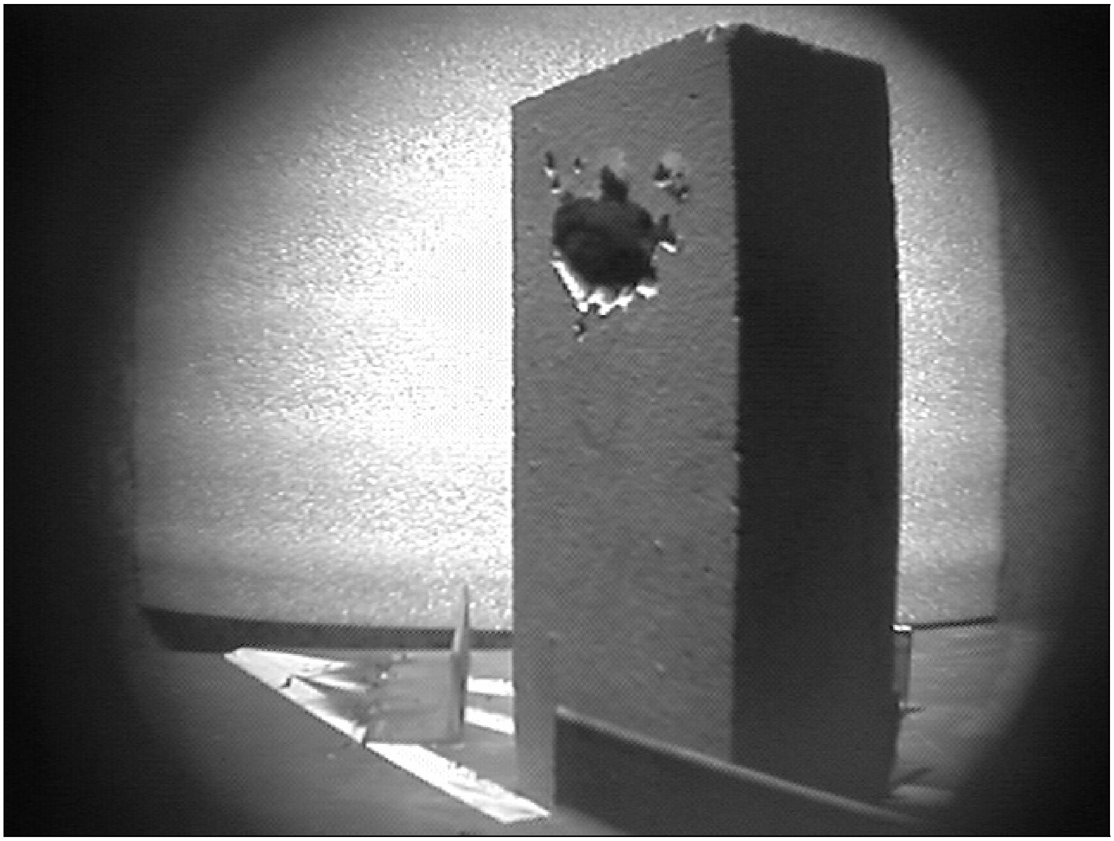
IMAGE 1	IMAGE 2	BLOB	PIXEL	% DIFF	ANGLE
cntr90	crck90	12	374		90
cntr60	crck60	13	438	14.61%	60
cntr45	crck45	17	833	55.10%	45
cntr30	crck30	18	753	50.33%	30

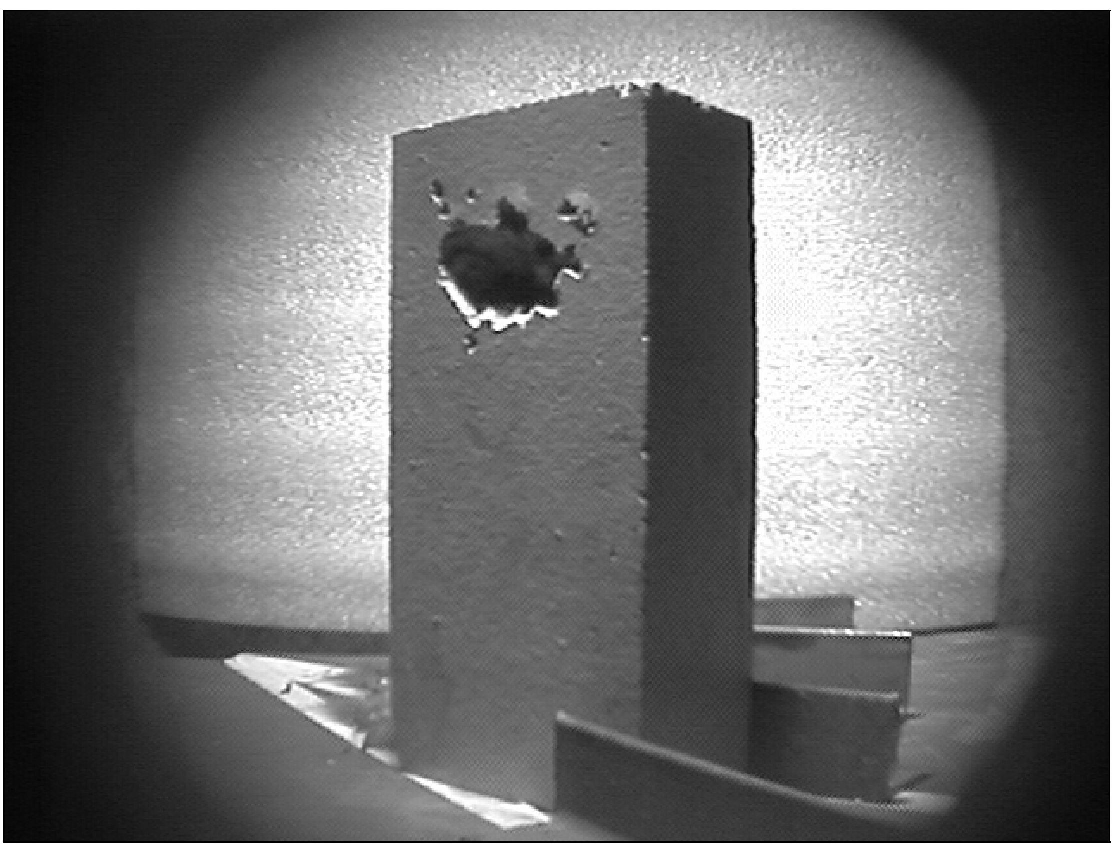


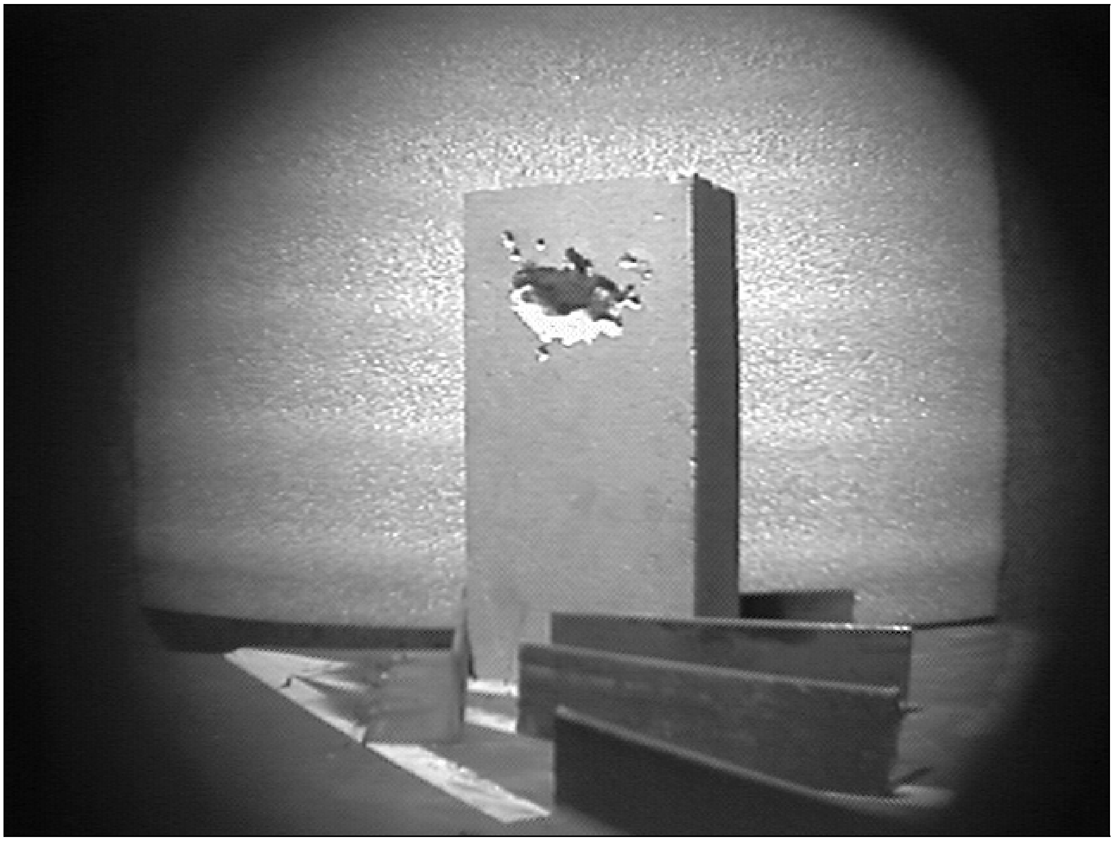


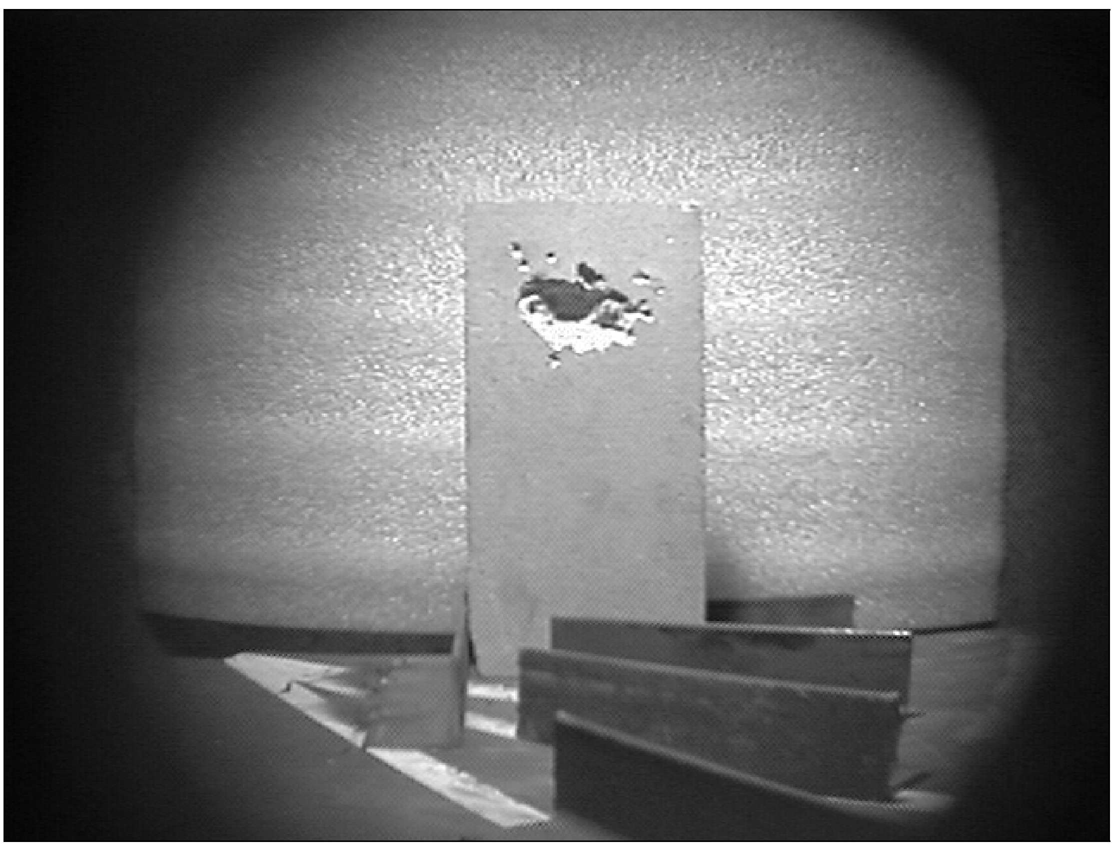






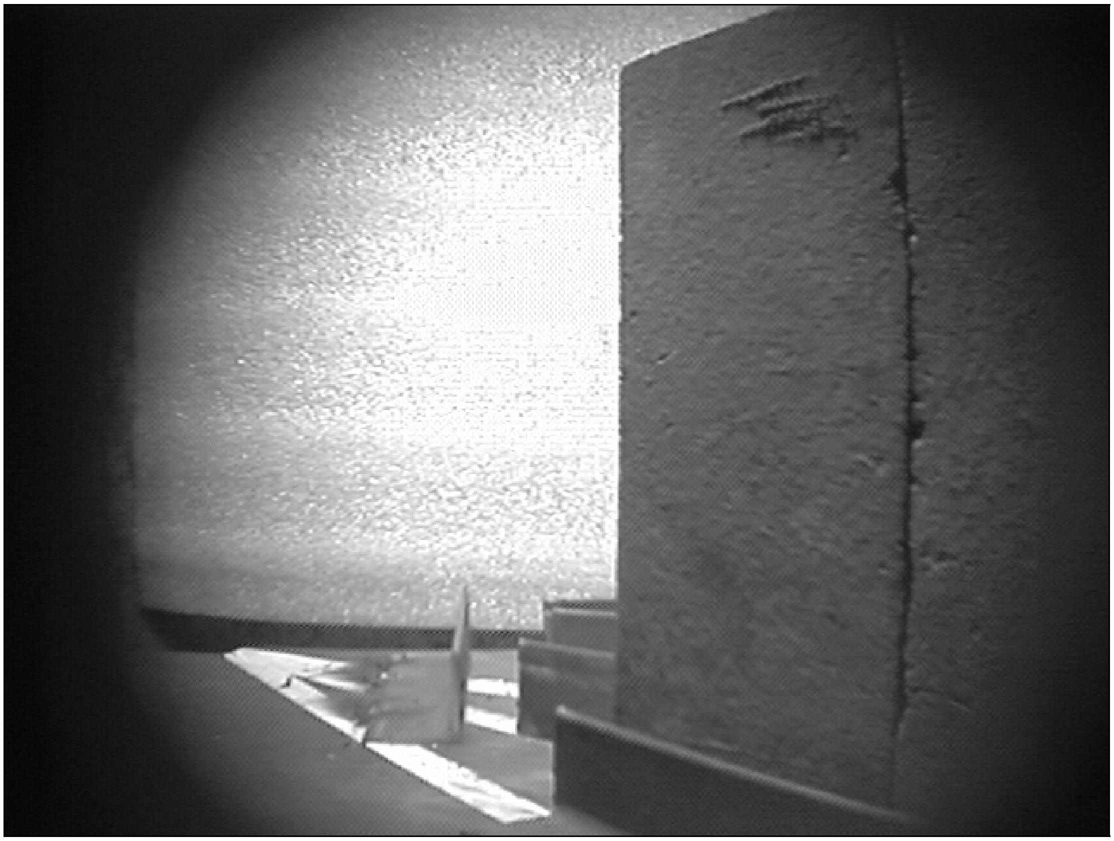


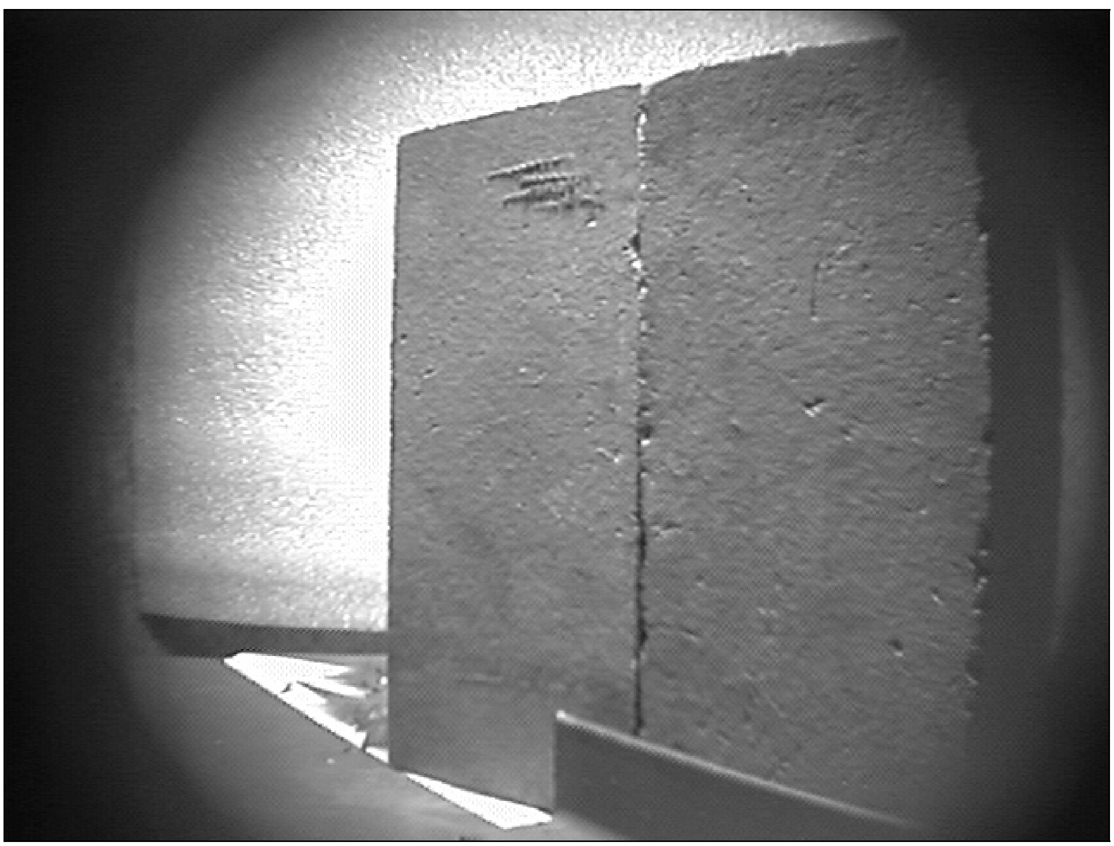


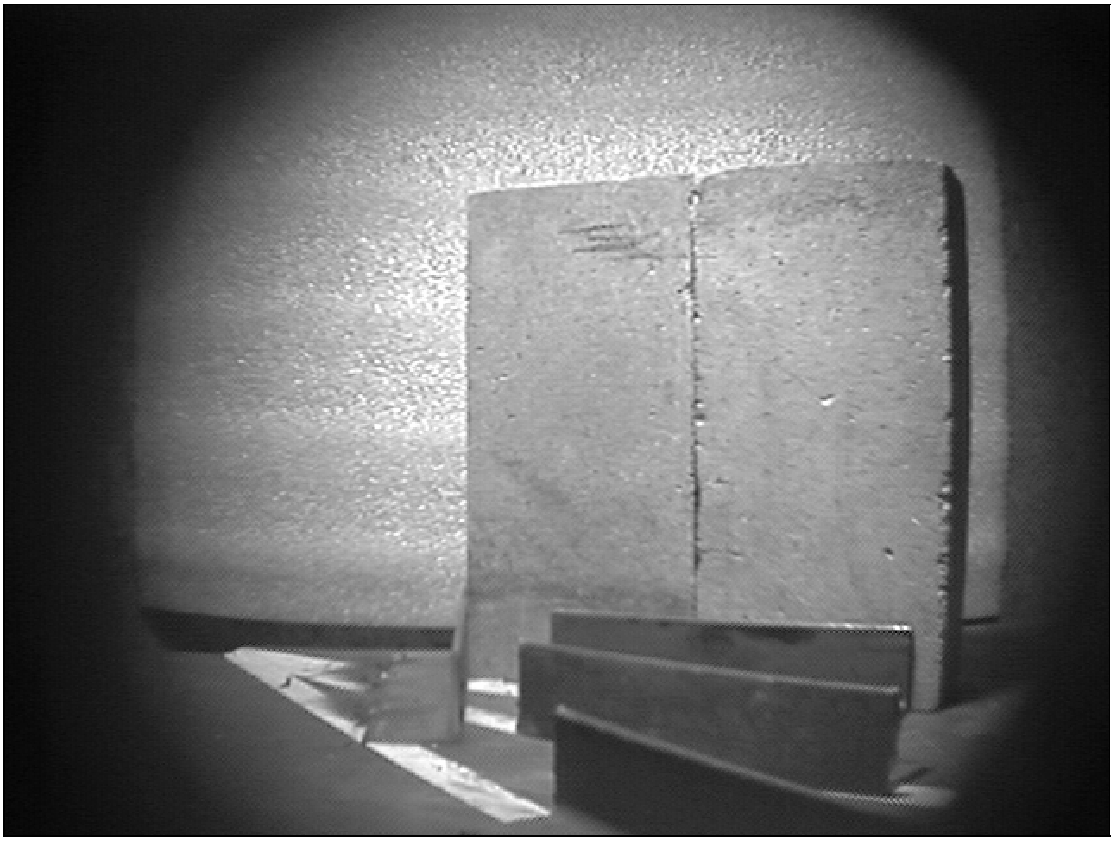


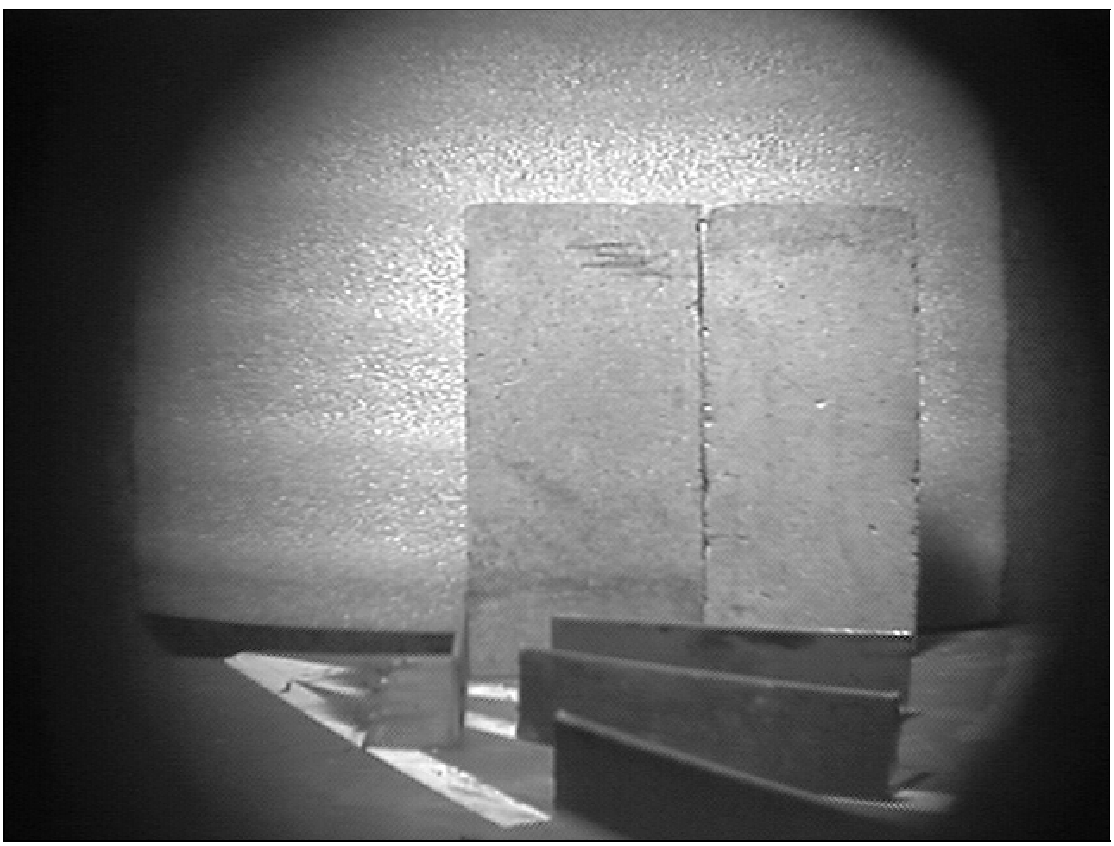
Erosion Damage Run

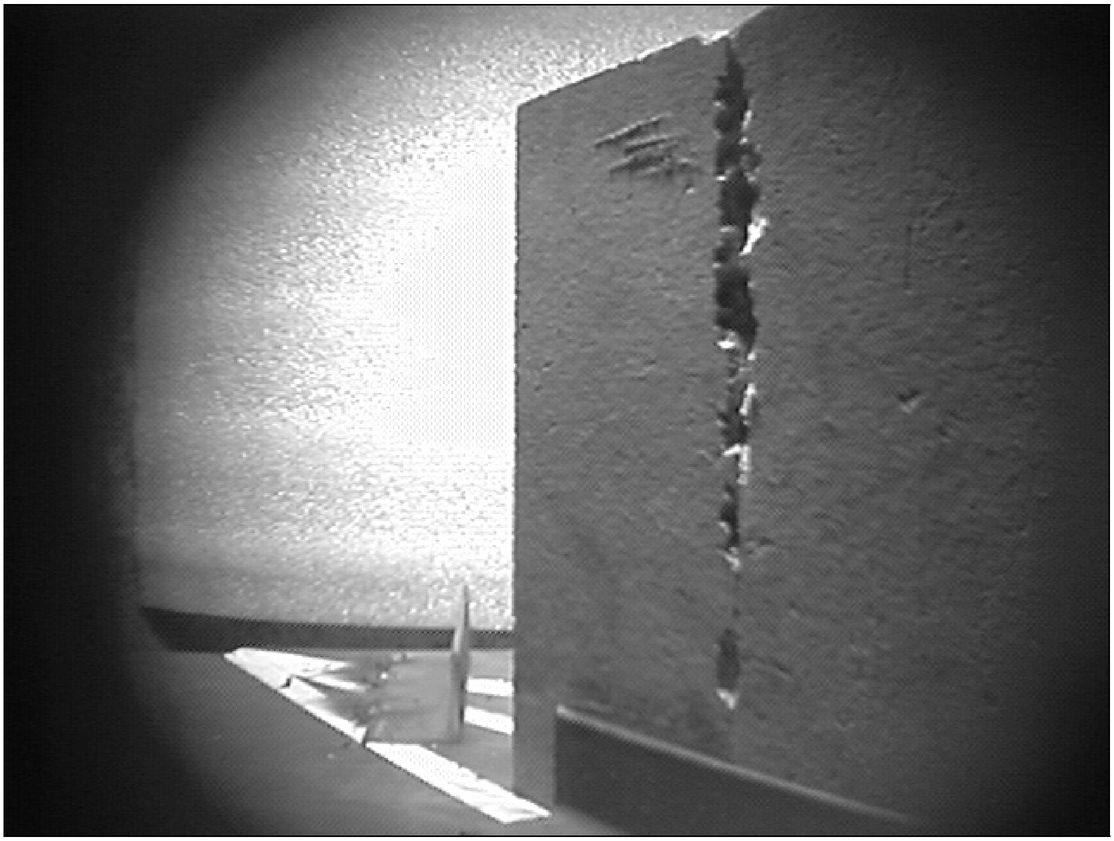
IMAGE 1	IMAGE 2	BLOB	PIXEL	% DIFF	ANGLE
cntr90	por90	11	2070		90
cntr60	por60	8	2340	11.54%	60
cntr45	por45	14	2943	29.66%	45
cntr30	por30	18	2863	27.70%	30

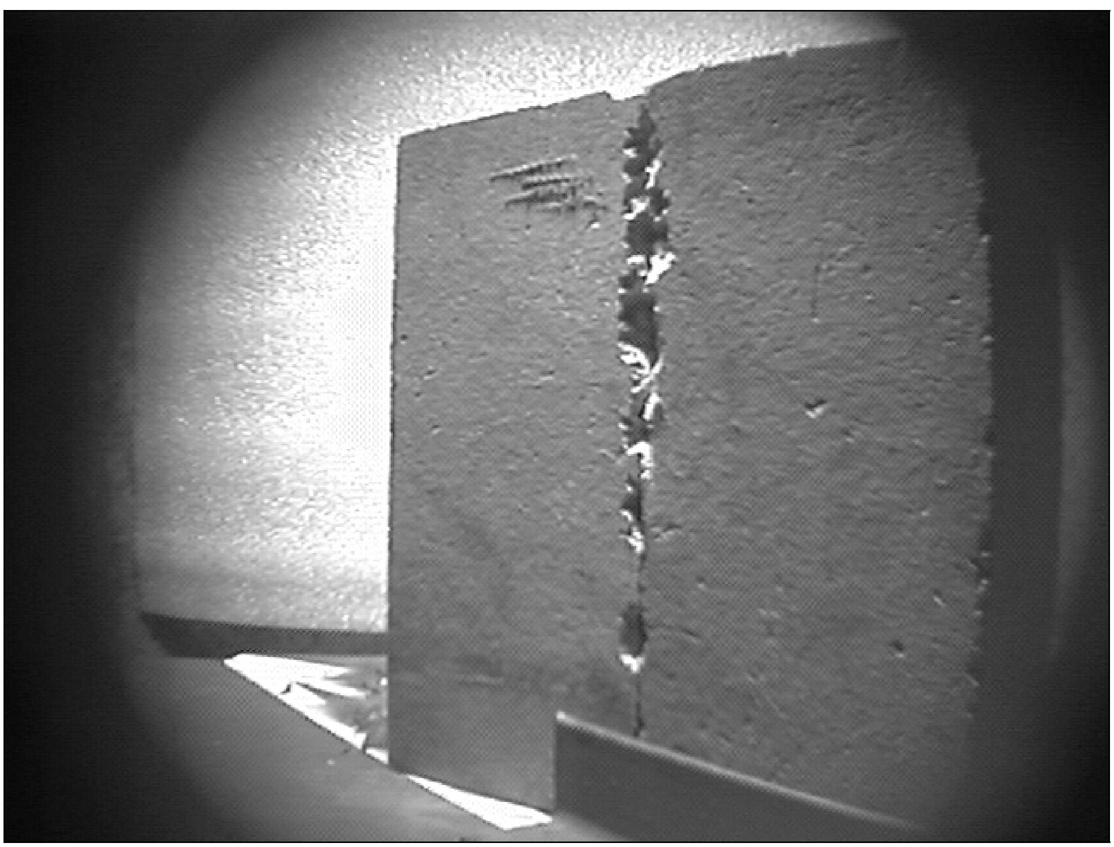


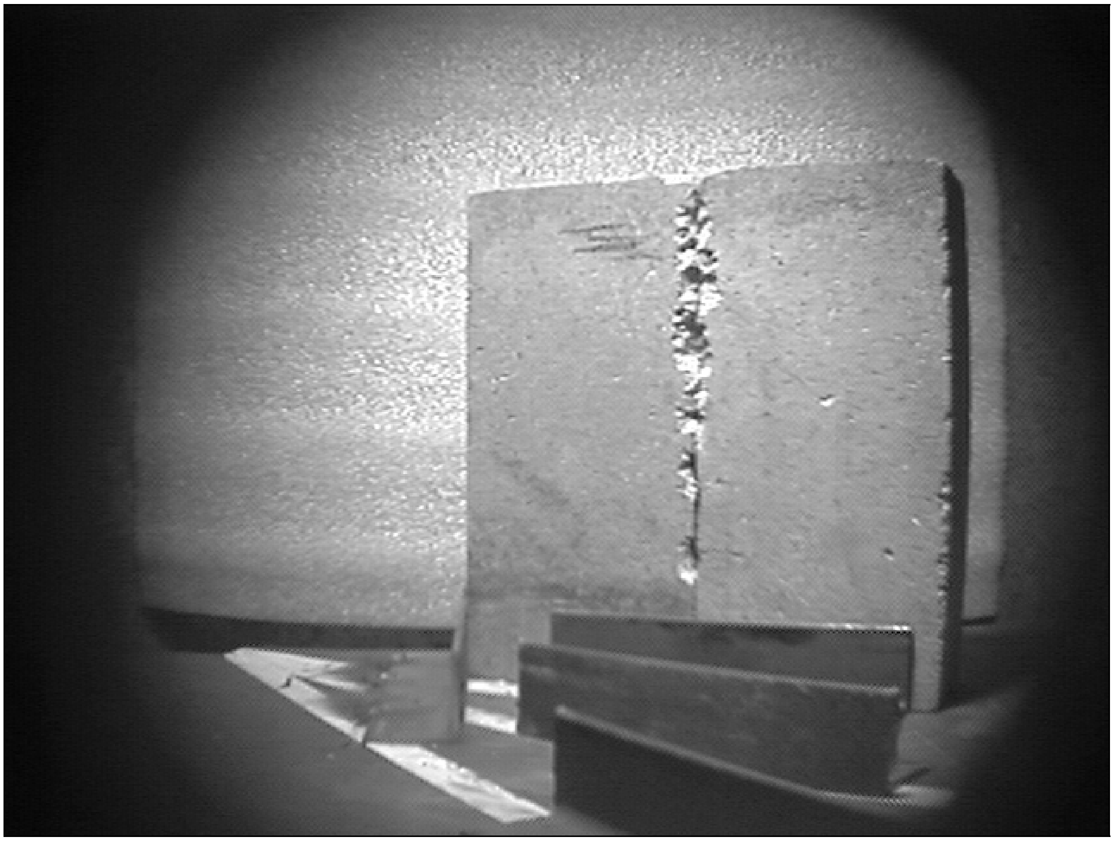


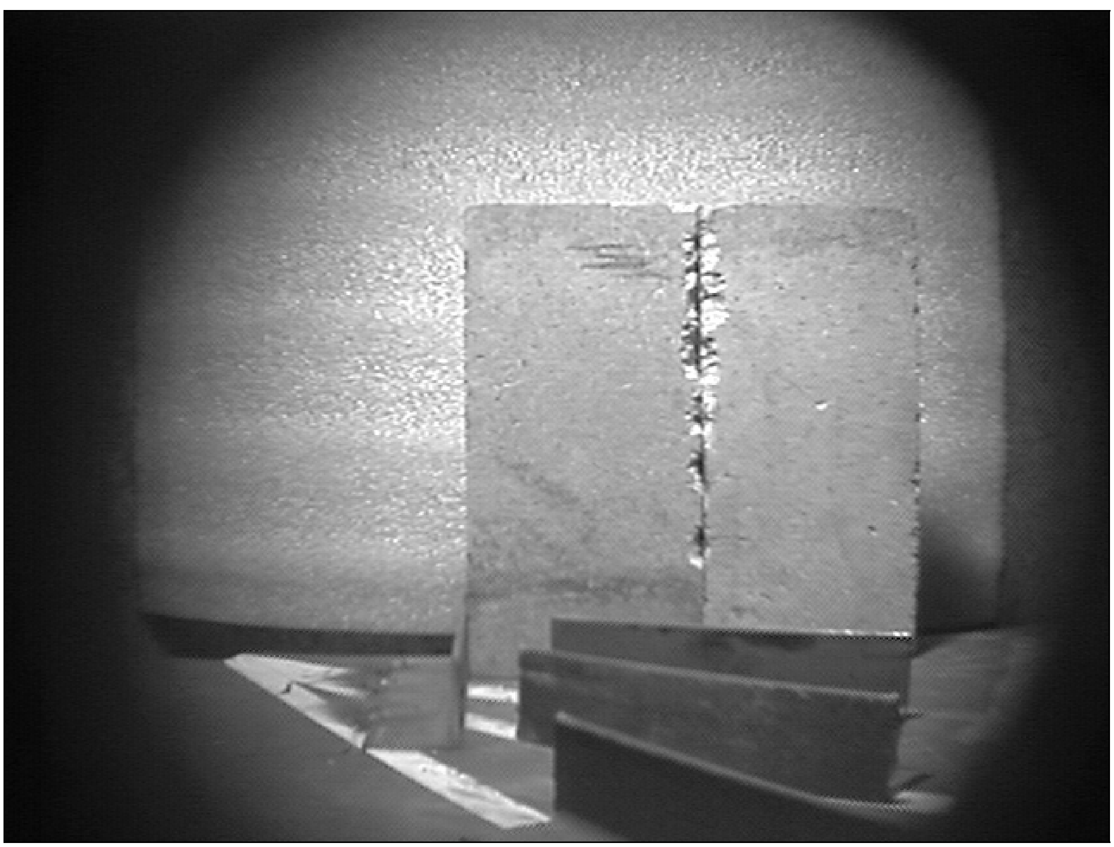






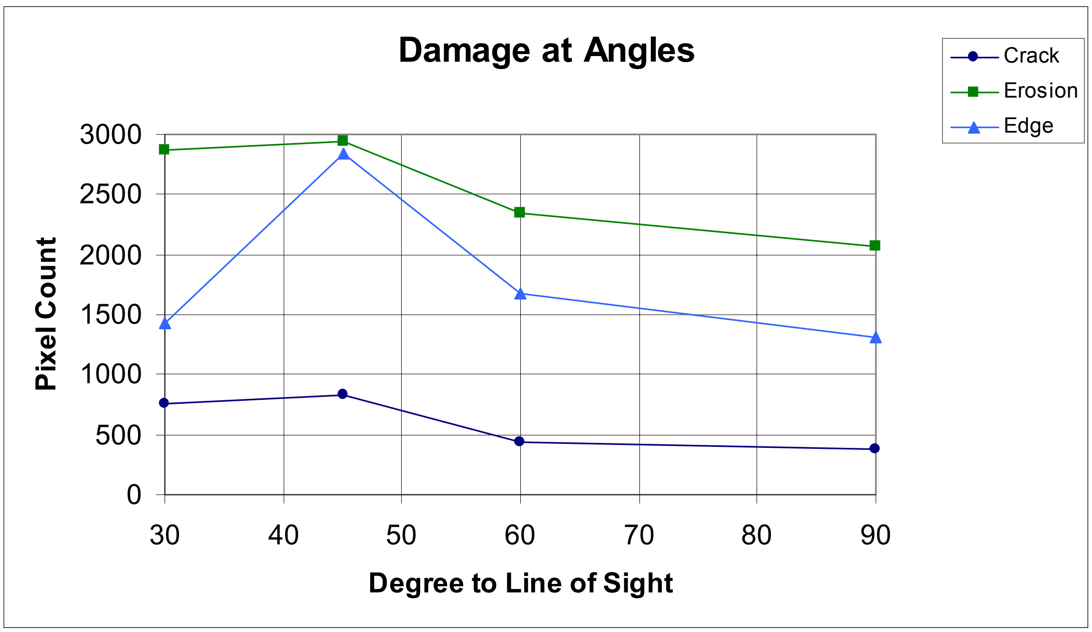






Edge Damage Run

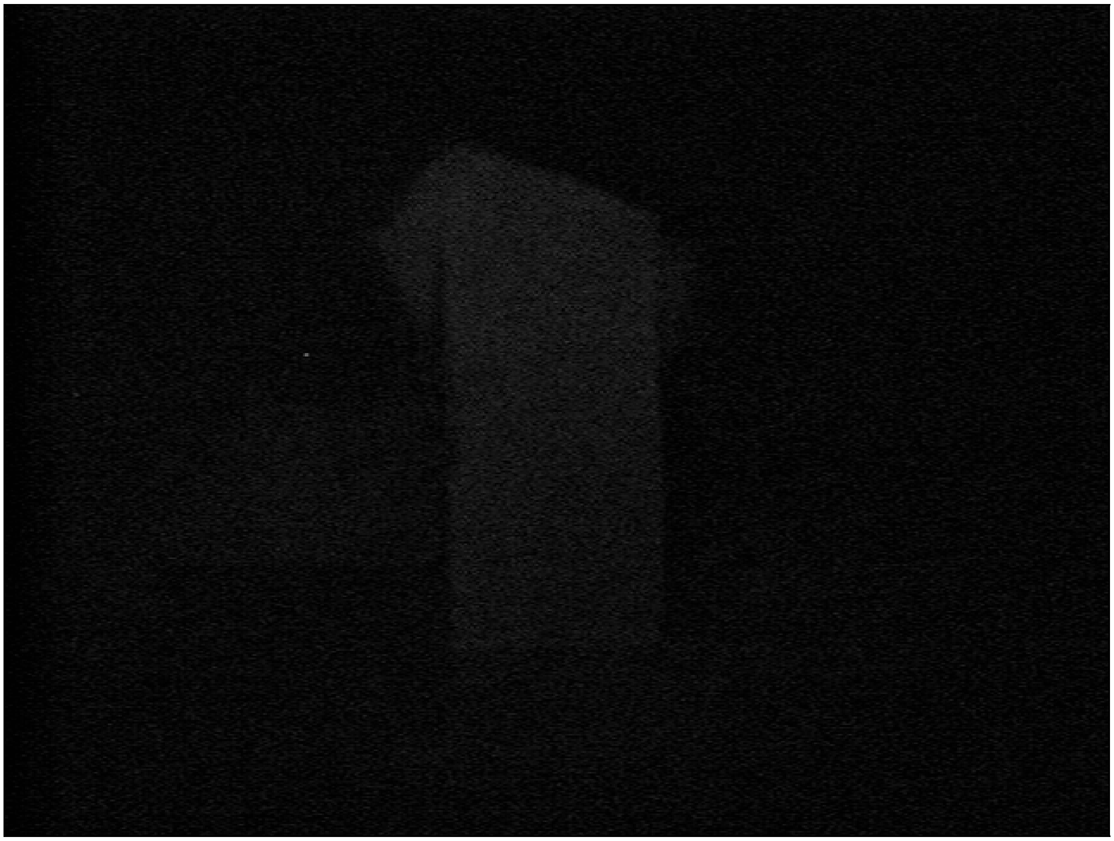
IMAGE 1	IMAGE 2	BLOB	PIXEL	% DIFF	ANGLE
cntr90	edg90	27	1315		90
cntr60	edg60	21	1675	21.49%	60
cntr45	edg45	37	2845	53.78%	45
cntr30	edg30	42	1430	8.04%	30

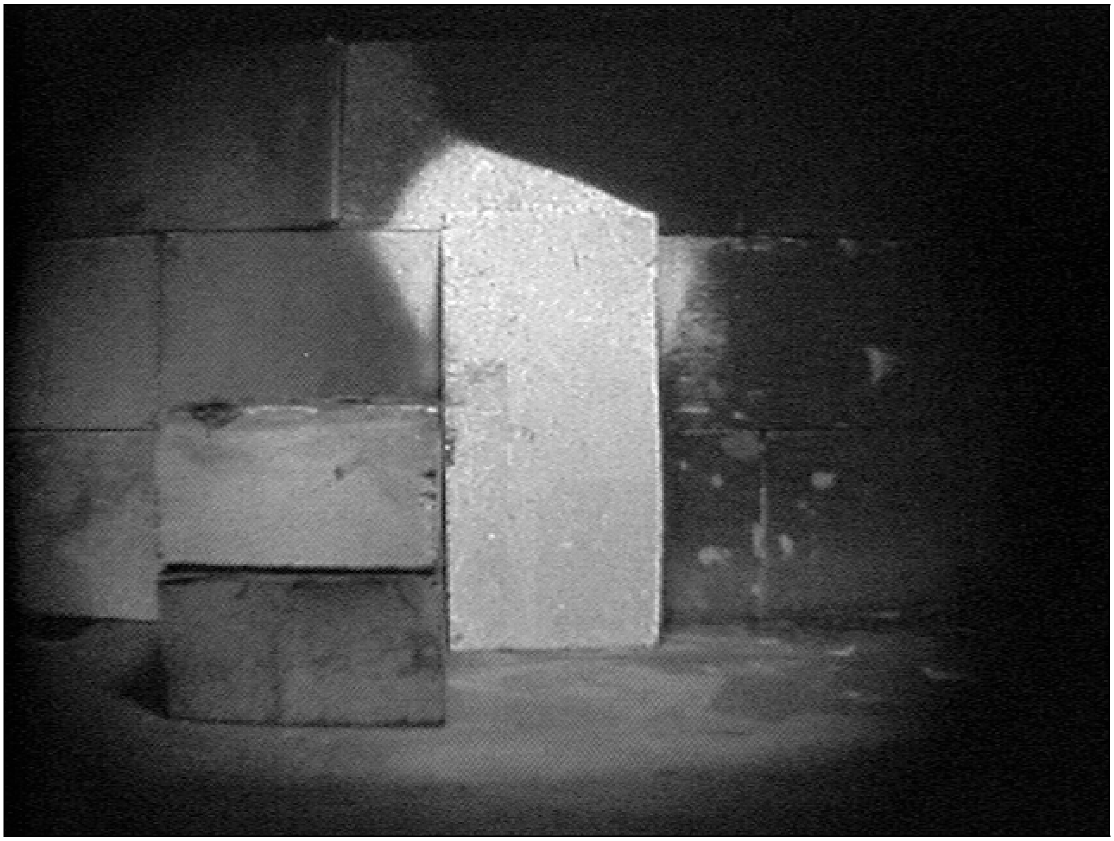


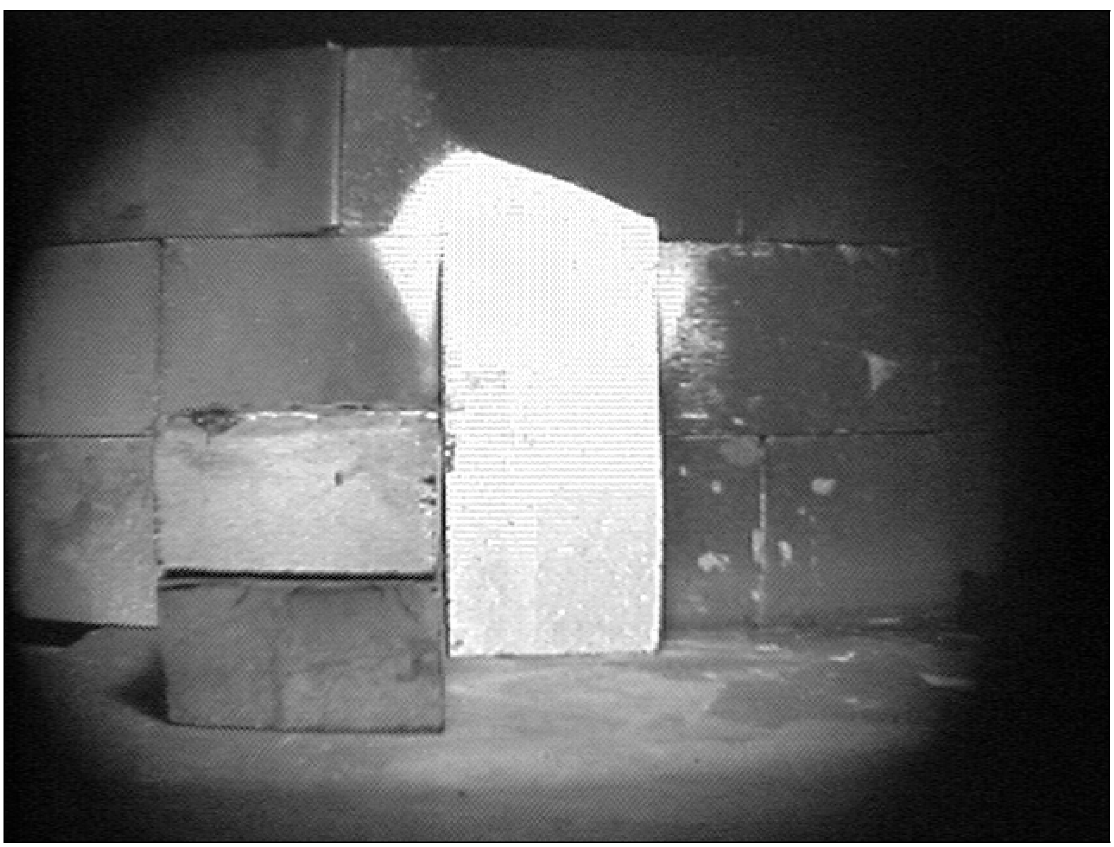
Damage at Angles
Crack
Erosion
Edge
Pixel Count
3000
2500
2000
1500
1000
500
0
30
40
50
60
70
80
90
Degree to Line of Sight

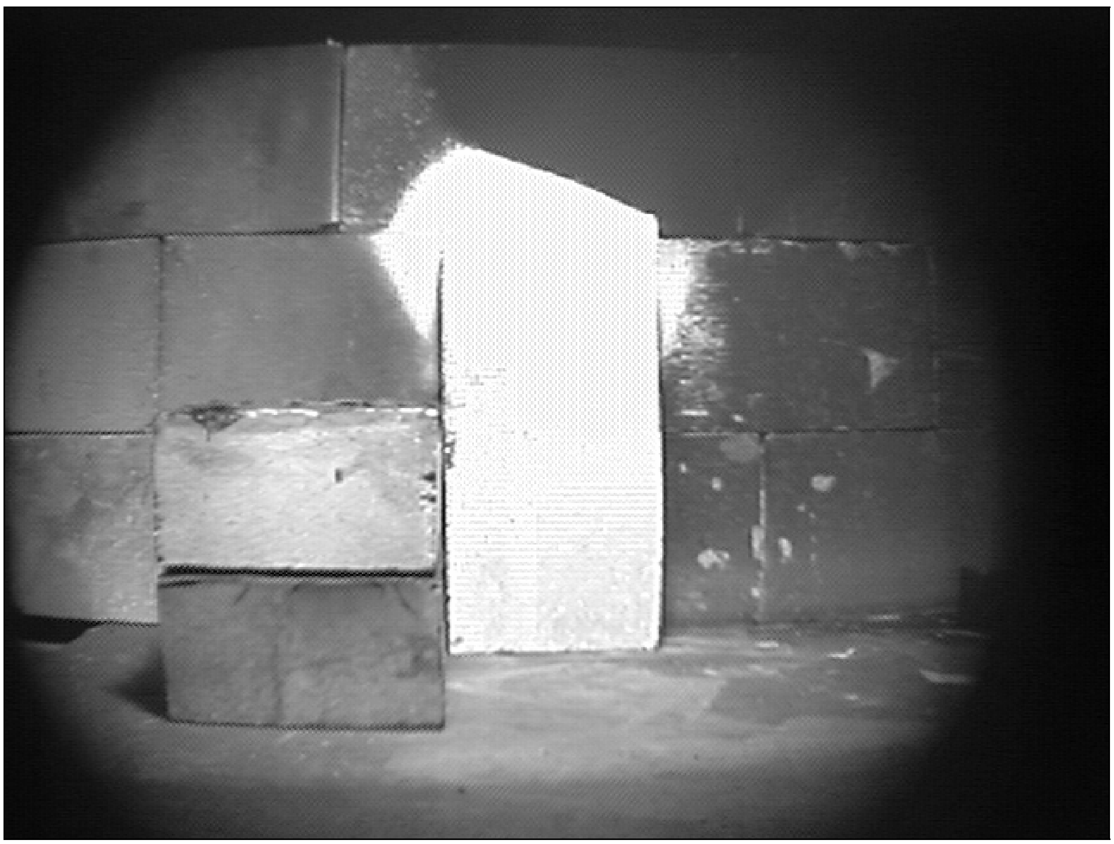
APPENDIX D

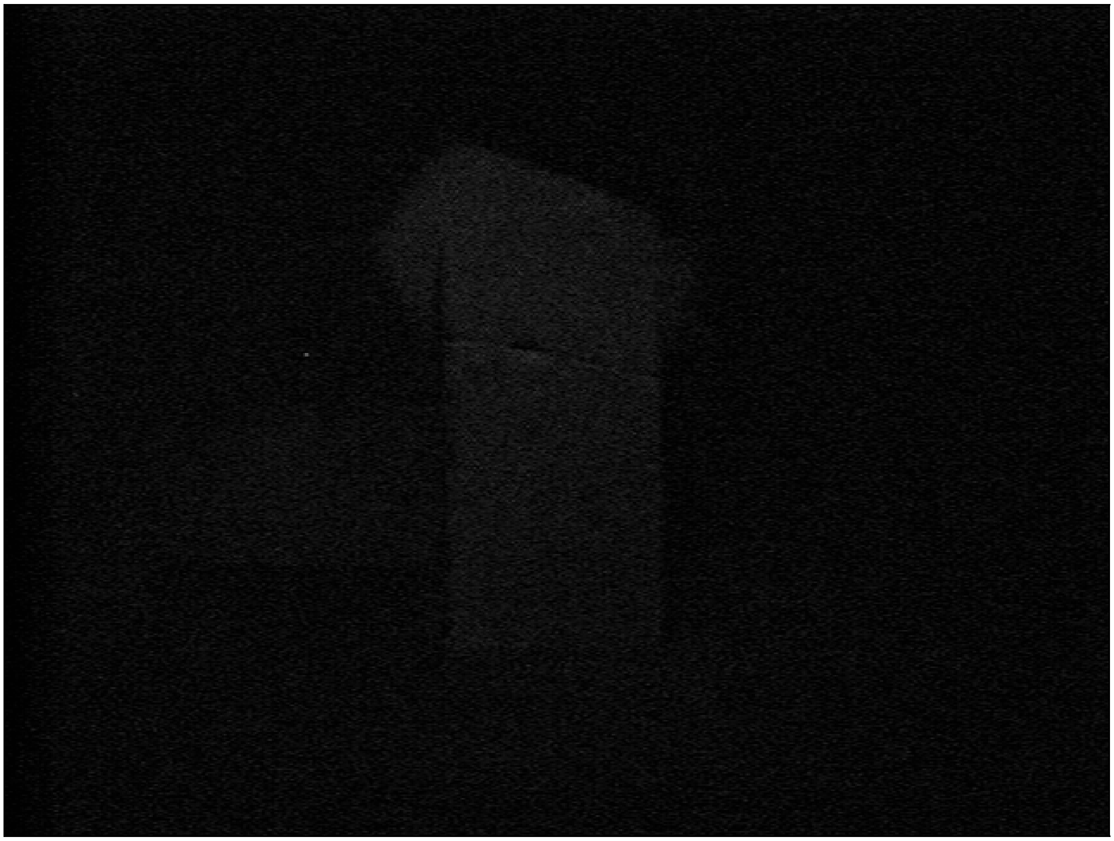
Low Light Capability Images and Data

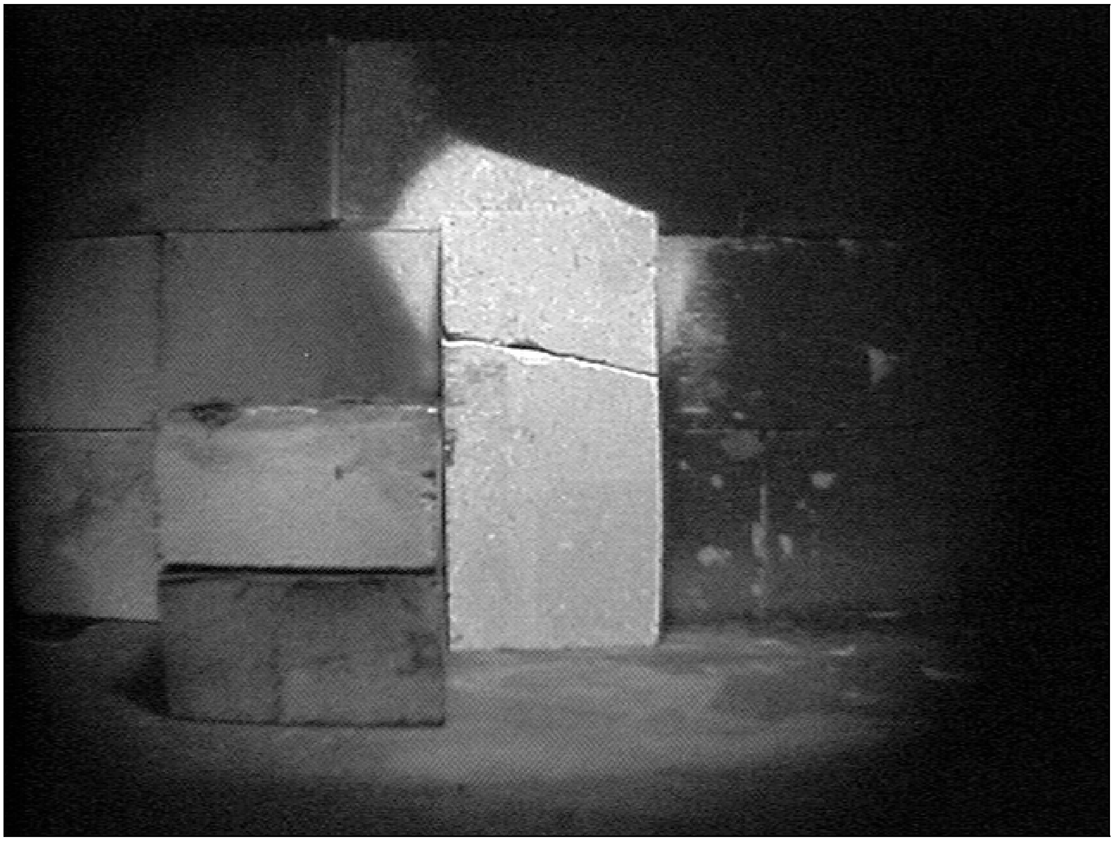


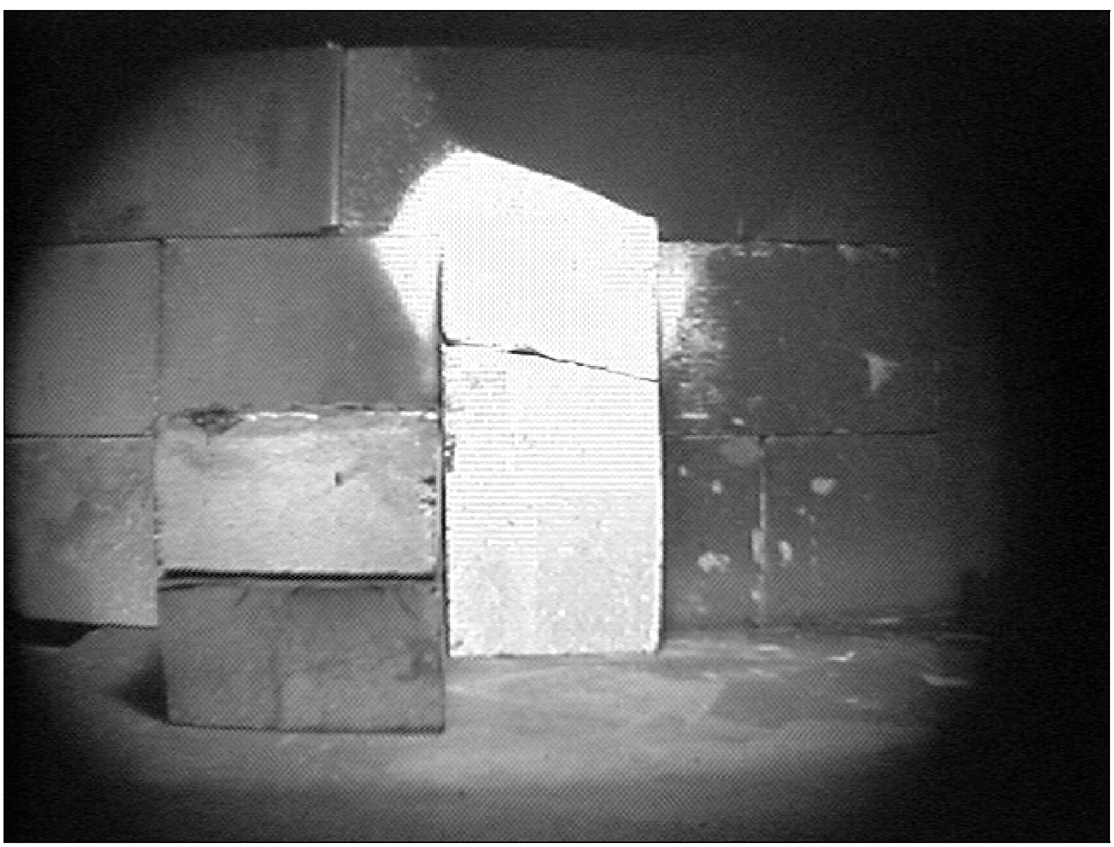


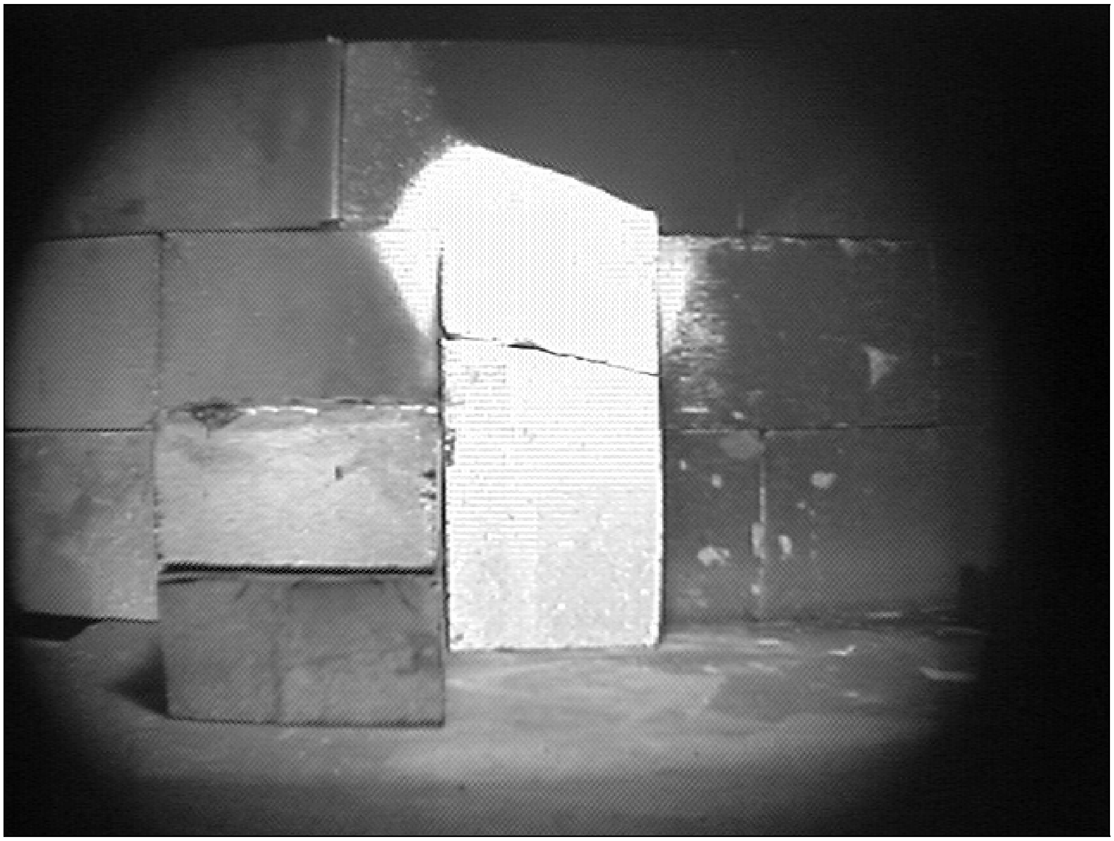






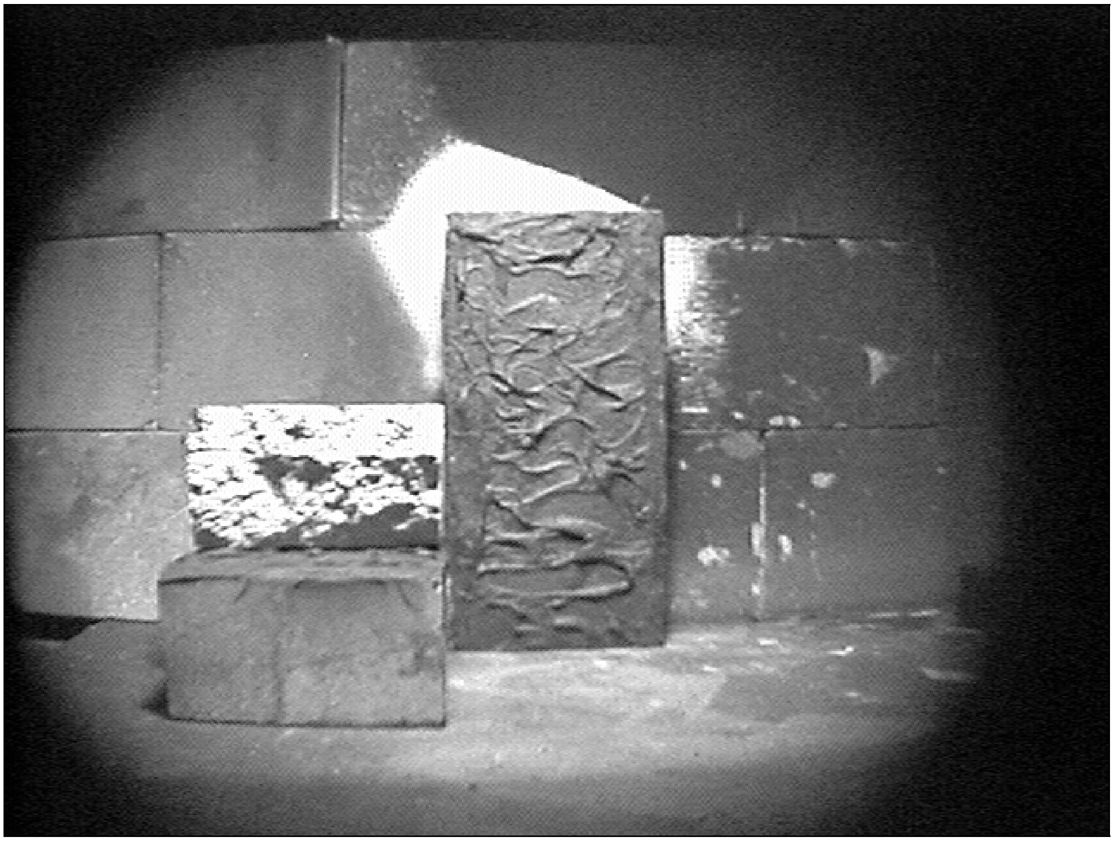


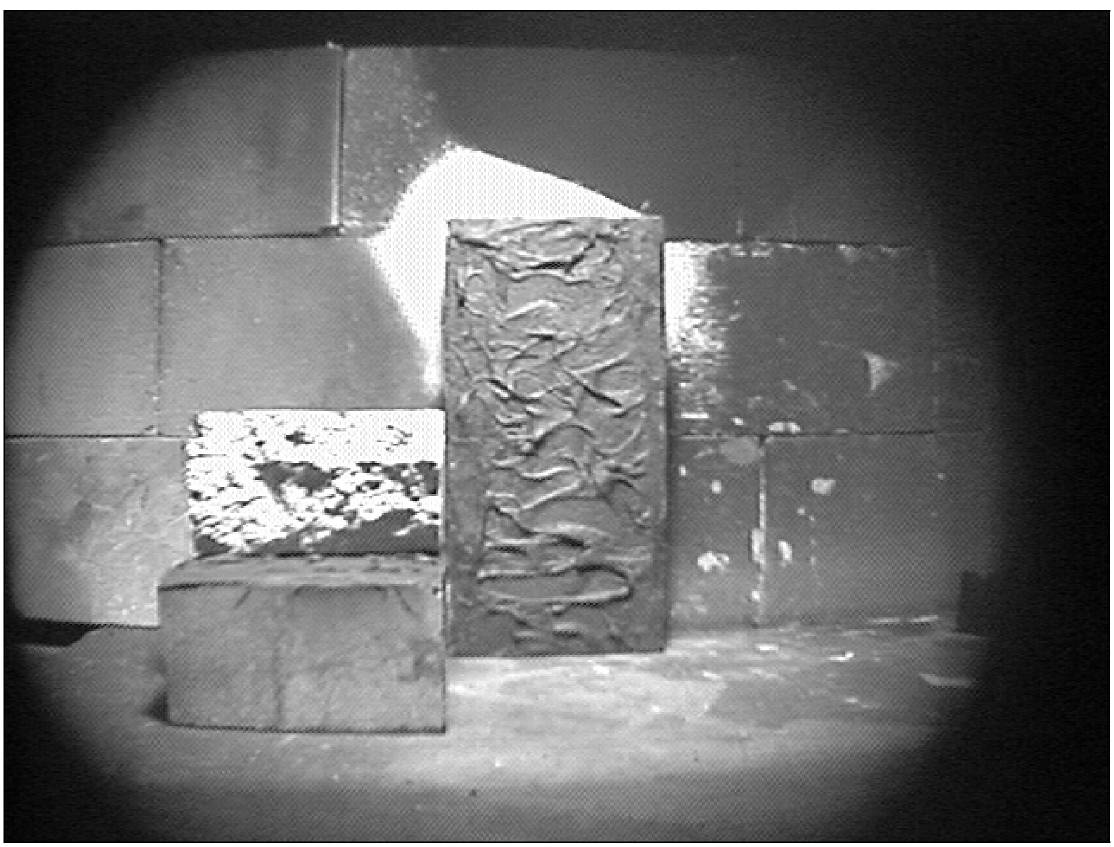


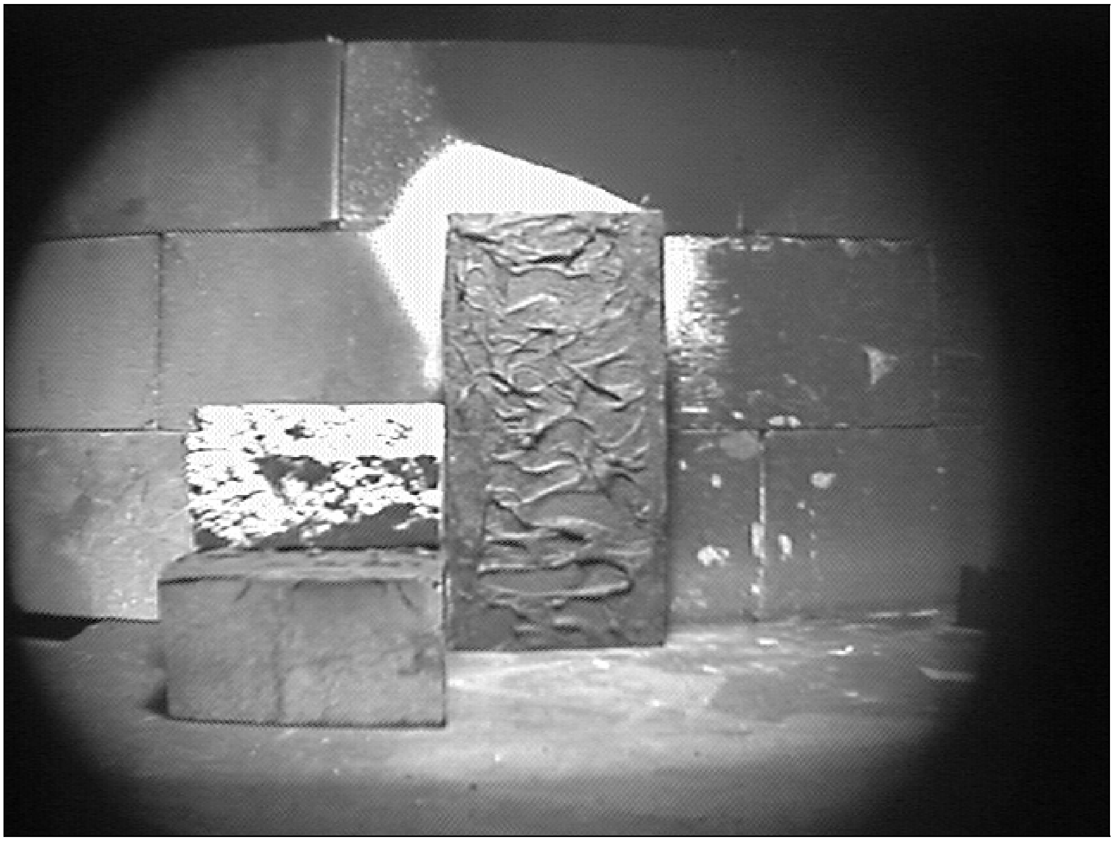


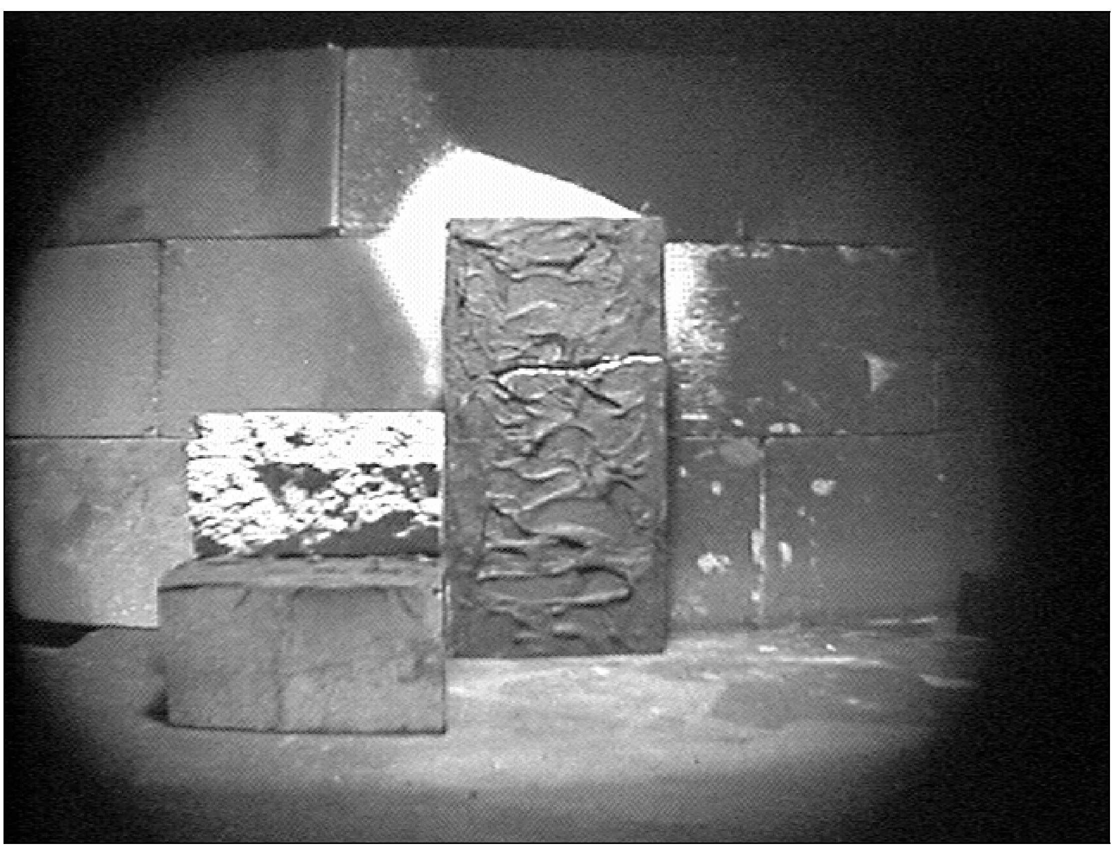
Cracked Brick

IMAGE 1	IMAGE 2	BLOB	PIXEL	THRESHOLD	LUM(cd/m^2)
cntr40	crck40	3	32	25	3
cntr60	crck60	3	583	40	28
cntr80	crck80	5	256	40	55
cntr100	crck100	5	264	40	109
cntr120	crck120	3	318	40	213
cnrt140	crck140	4	282	40	357



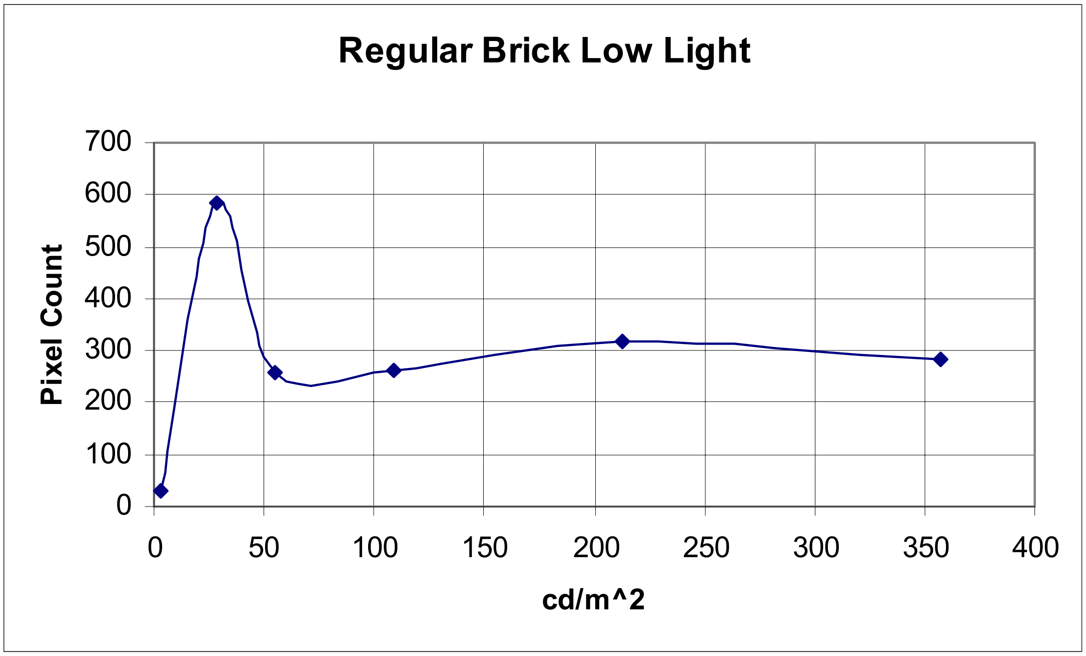


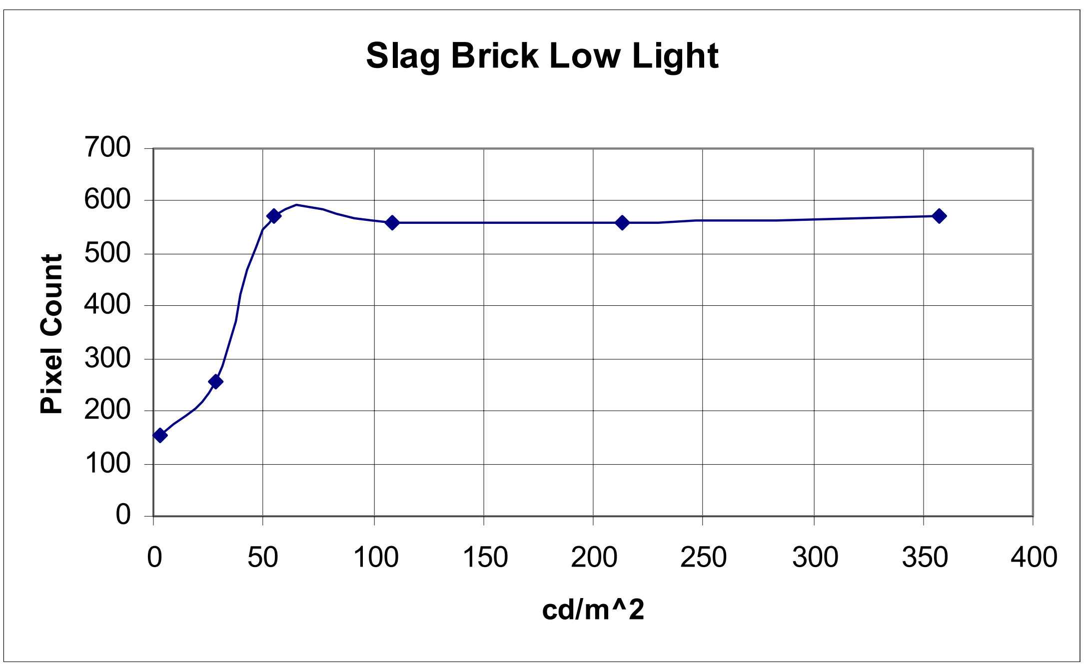


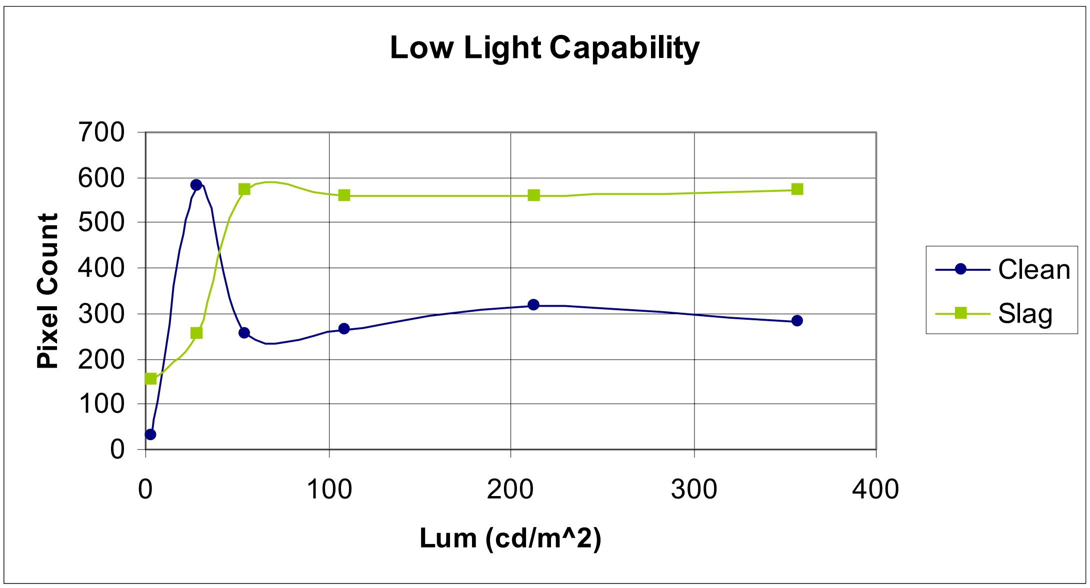


Slag Cracked Brick

IMAGE 1	IMAGE 2	BLOB	PIXEL	THRESHOLD	LUM(cd/m^2)
cntr40	crck40	4	153	20	3
cntr60	crck60	9	255	50	28
cntr80	crck80	4	574	50	55
cntr100	crck100	3	560	50	109
cntr120	crck120	3	559	50	213
cnrt140	crck140	4	571	50	357

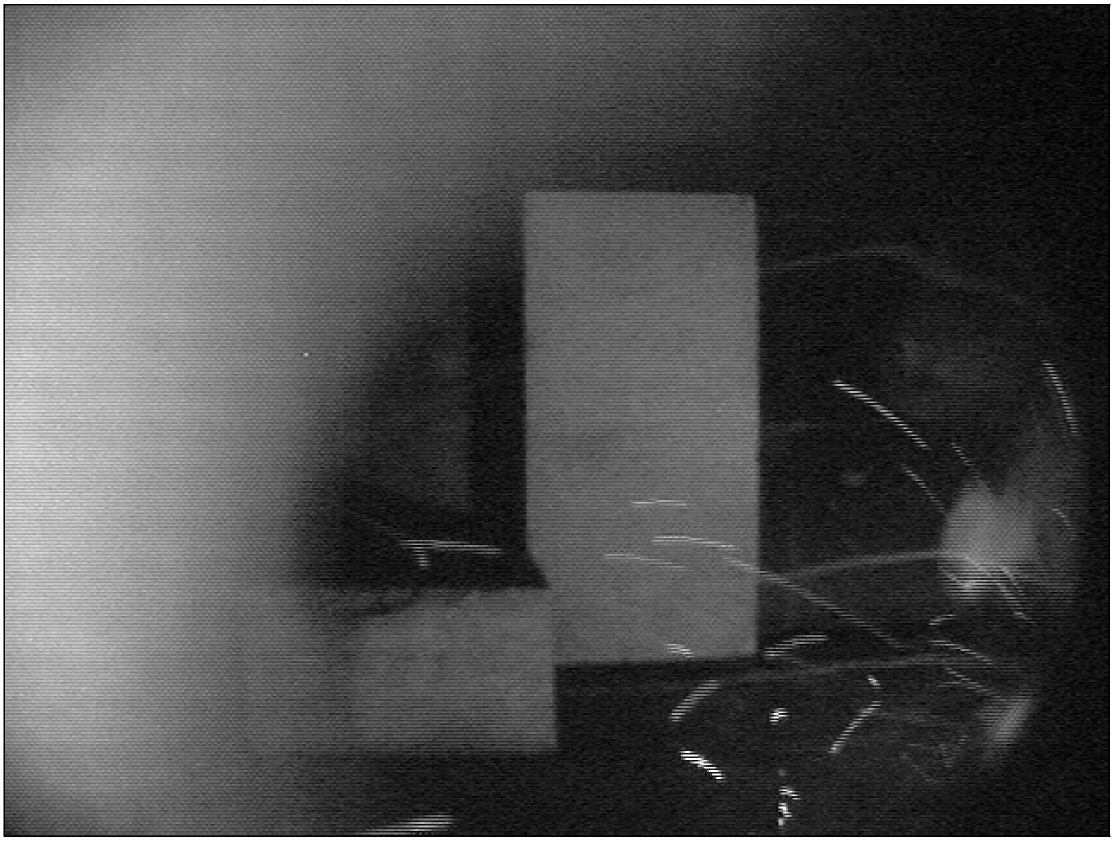

Regular Brick Low Light
Pixel Count
700
600
500
400
300
200
100
0
0
50
100
150
200
250
300
350
400
cd/m^2

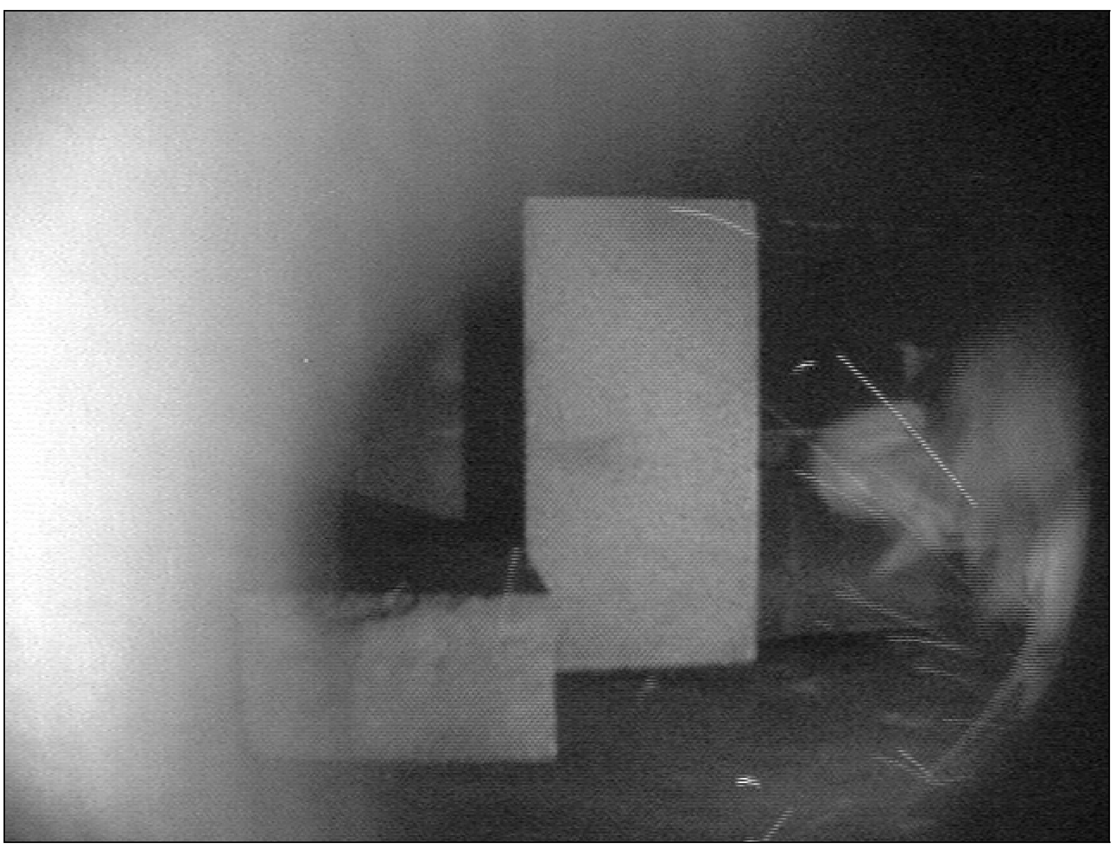

Slag Brick Low Light
Pixel Count
700
600
500
400
300
200
100
0
0
50
100
150
200
250
300
350
400
cd/m^2

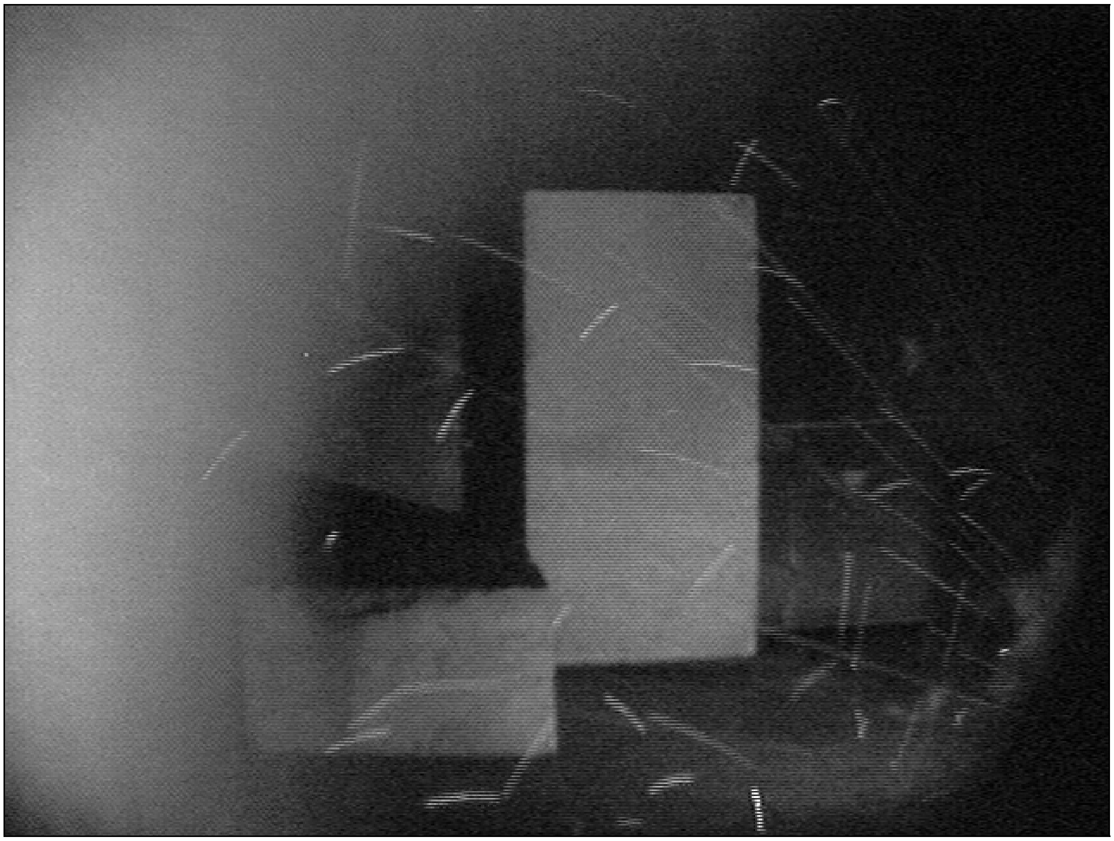

Low Light Capability
700
600
500
400
300
200
100
0
Pixel Count
0
100
200
300
400
Lum (cd/m^2)
Clean
Slag

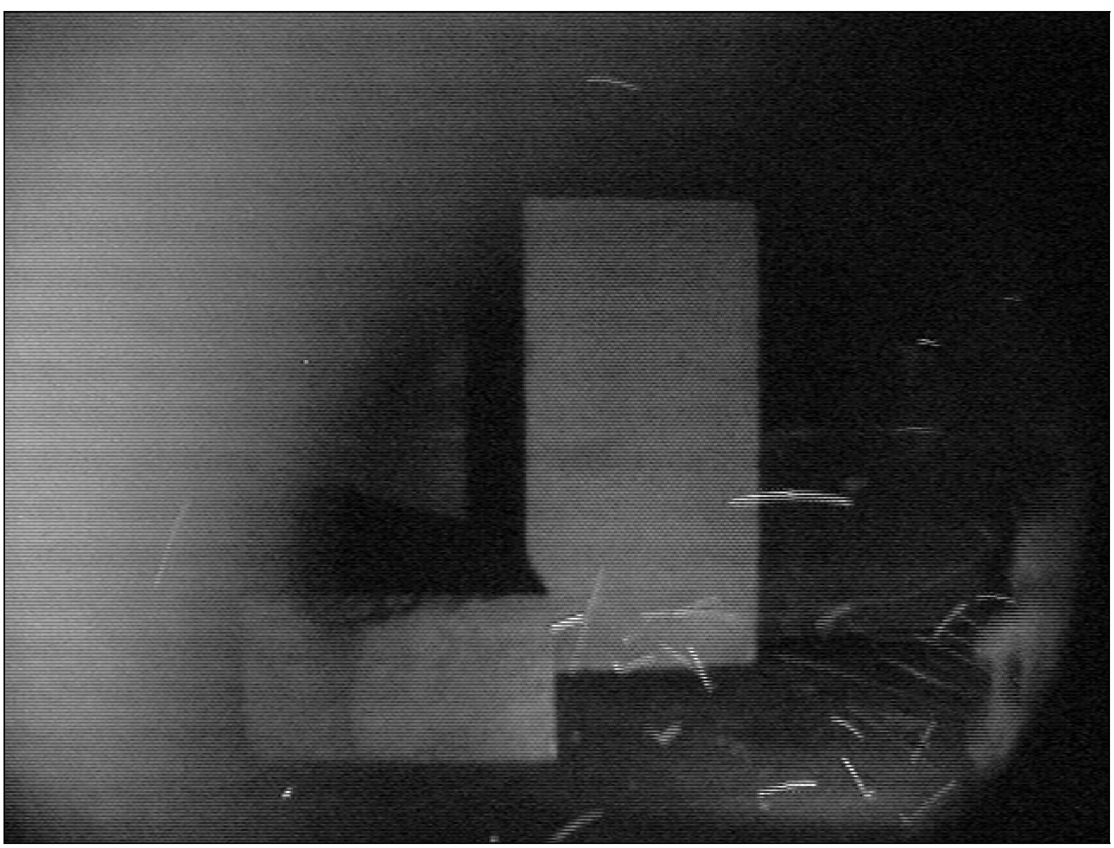
APPENDIX E

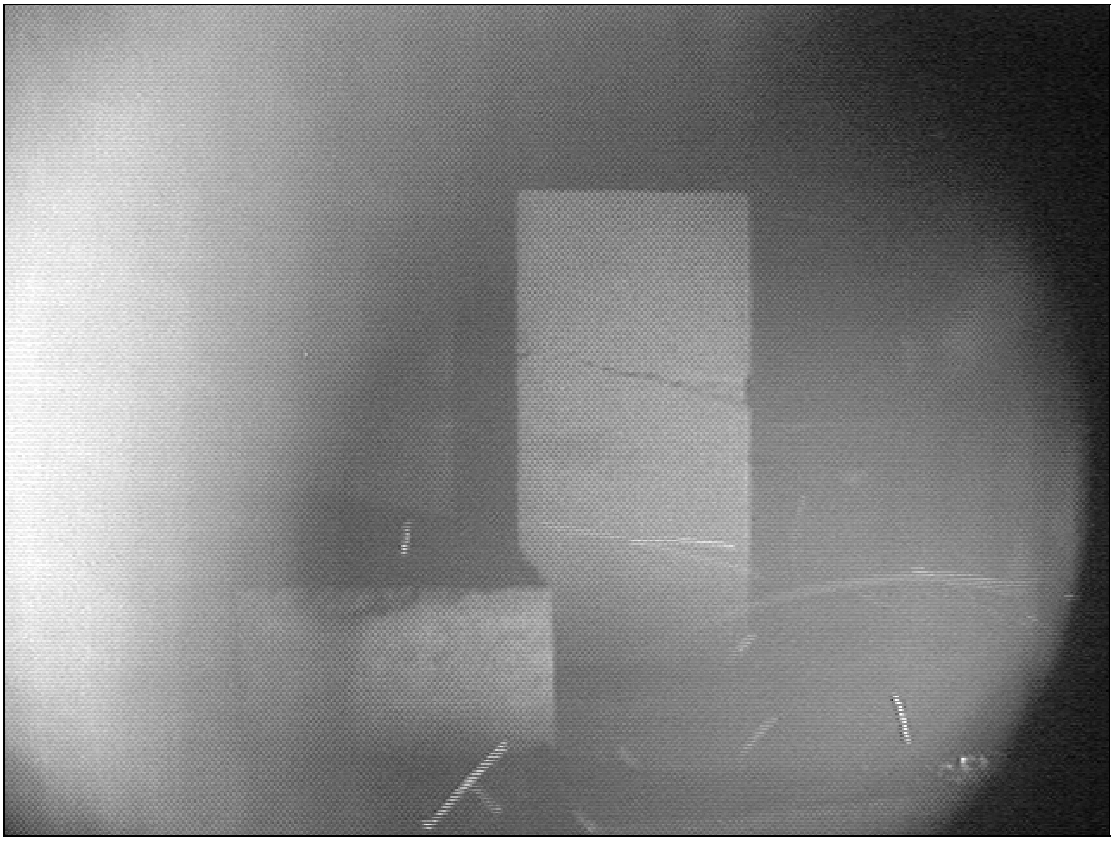
Intense Light Capability Images

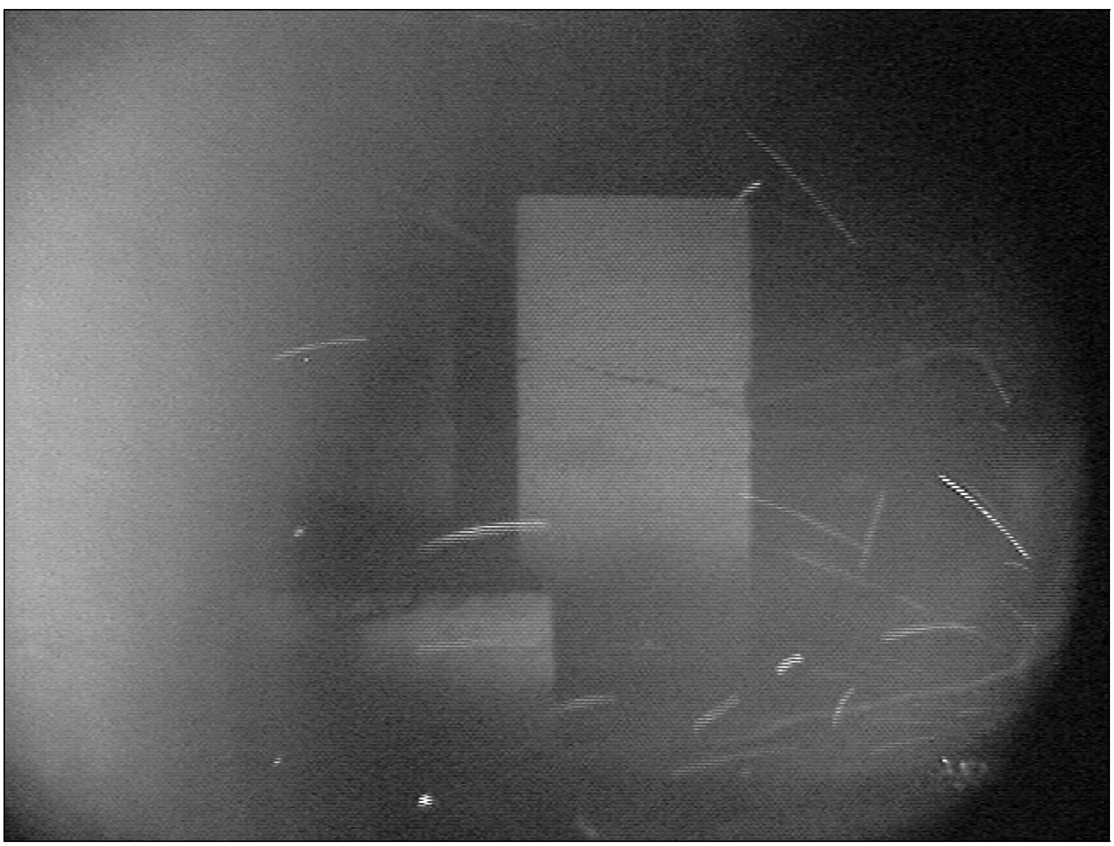


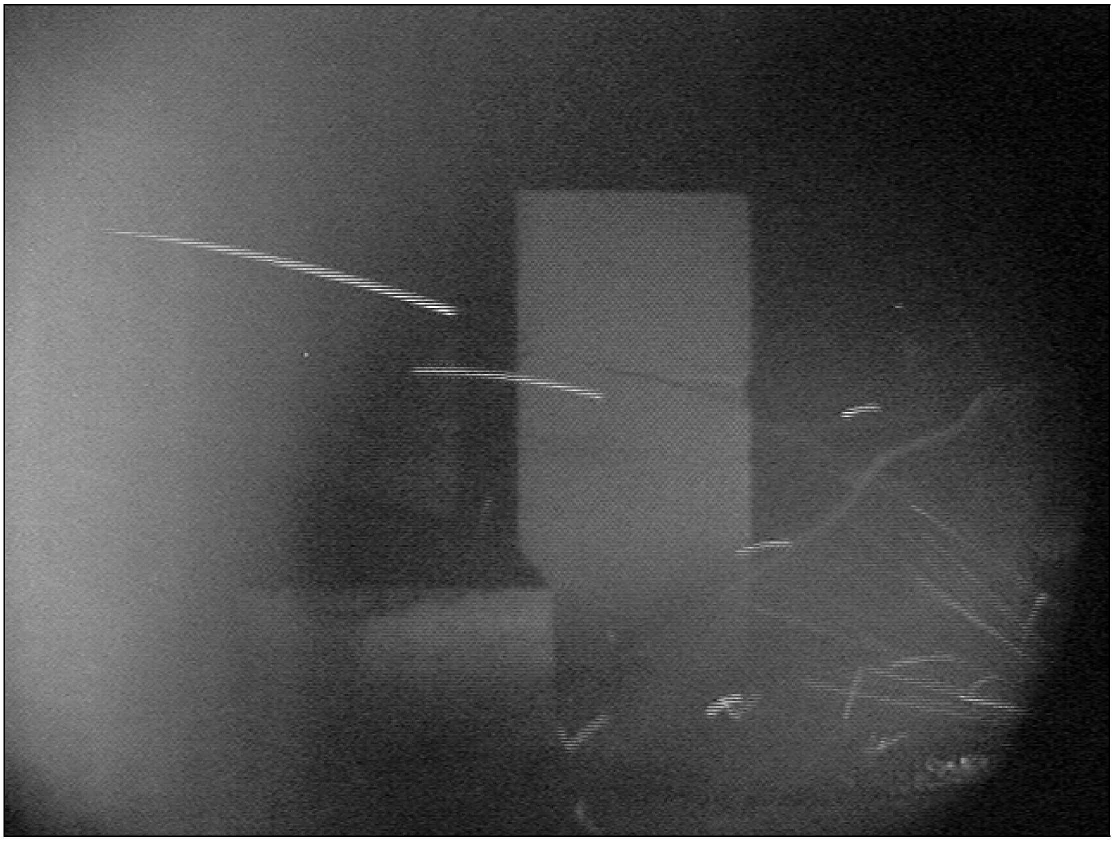


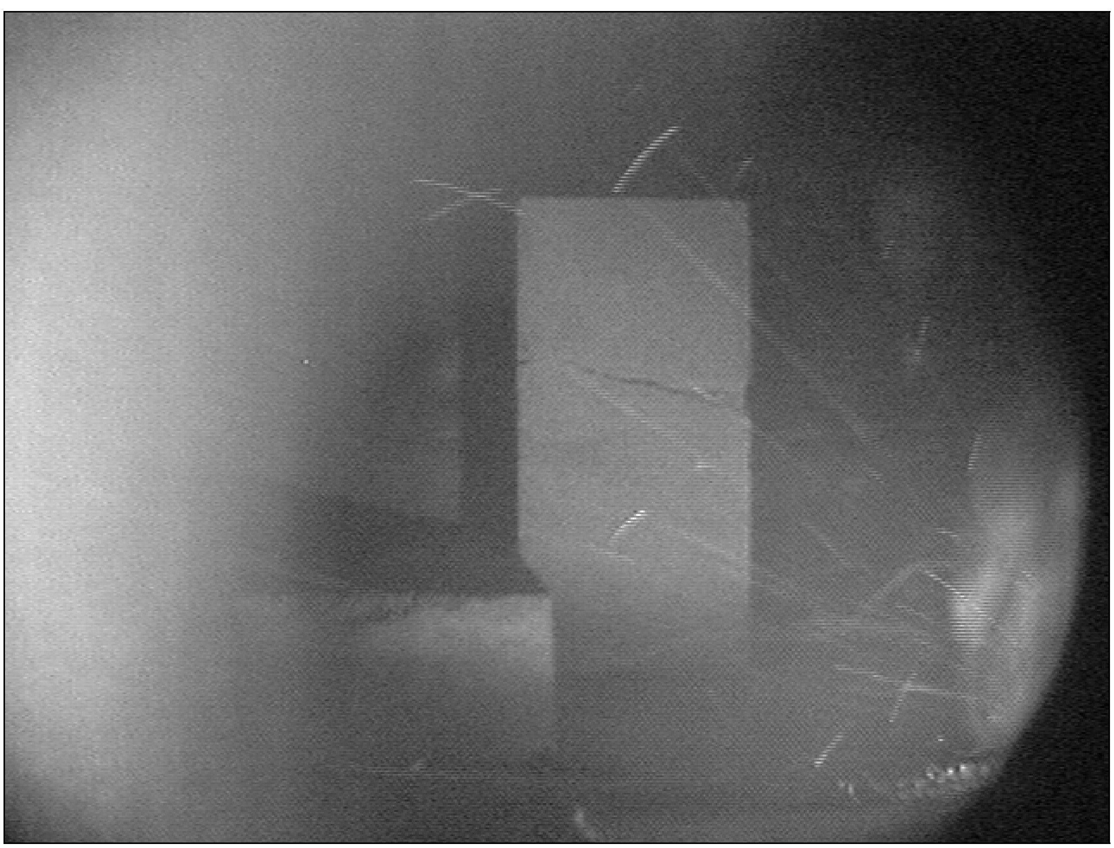


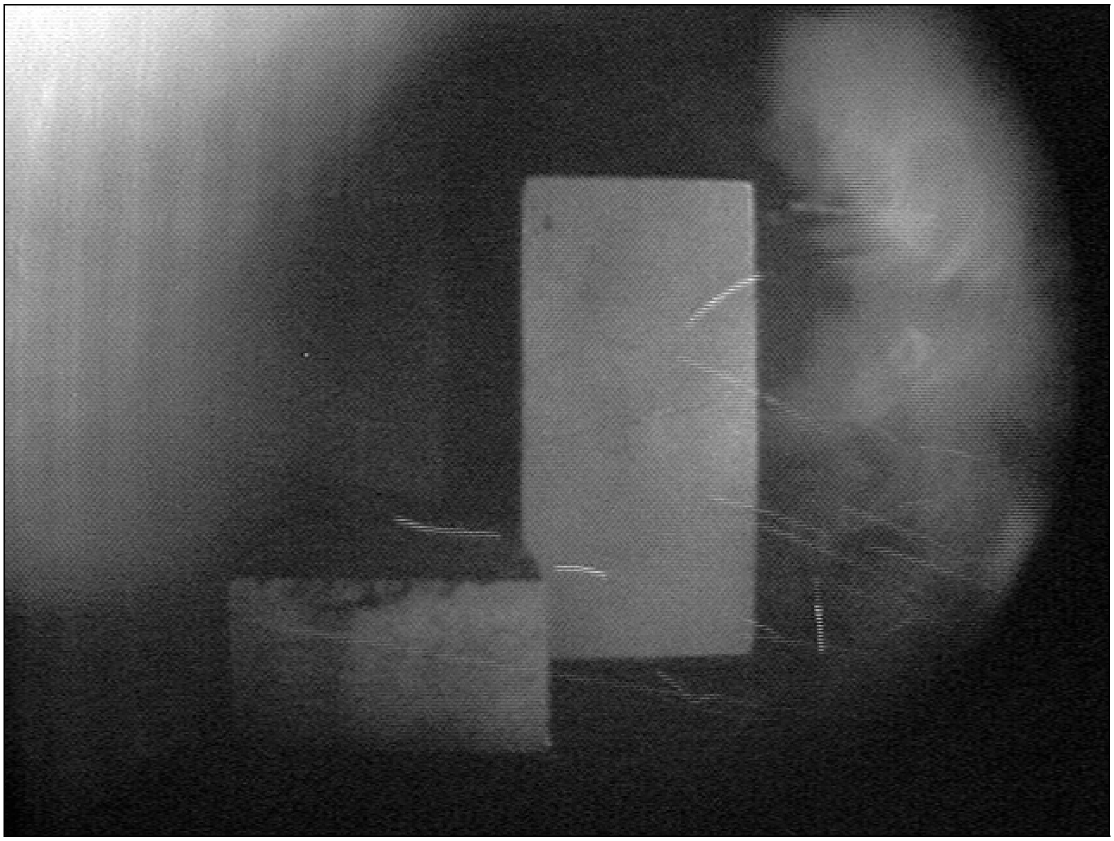


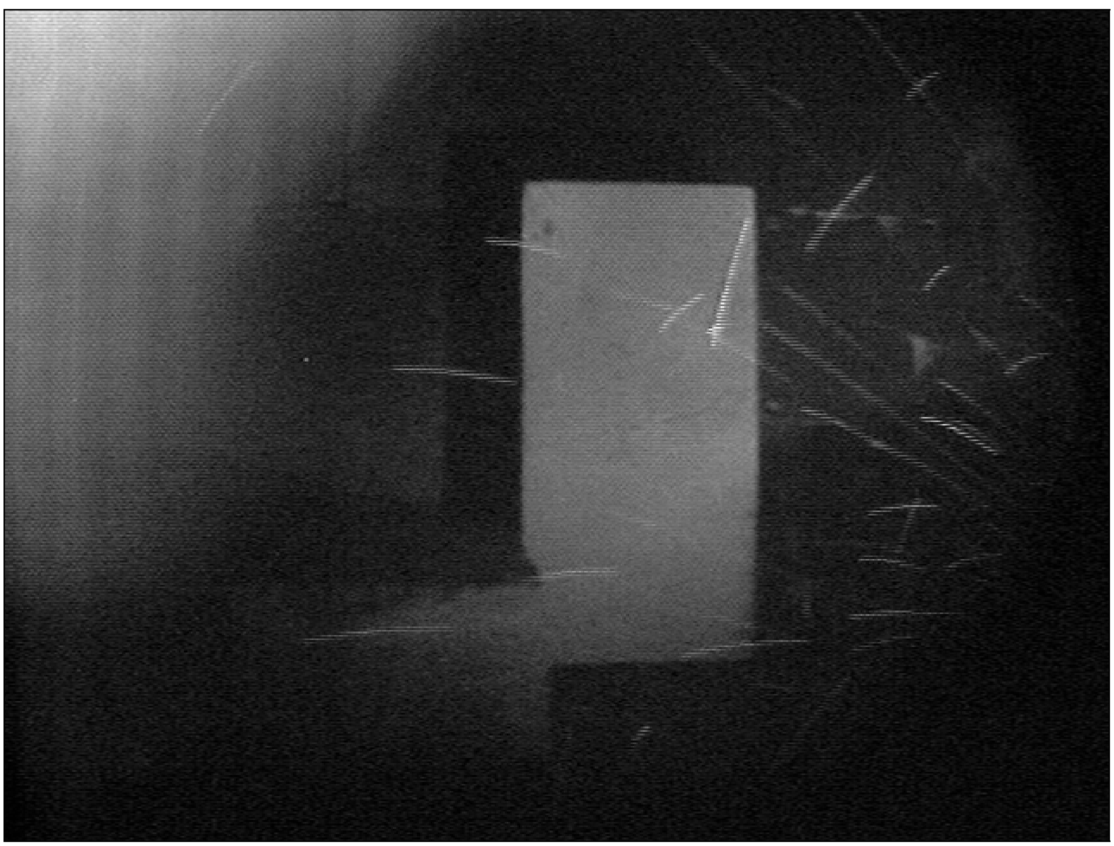


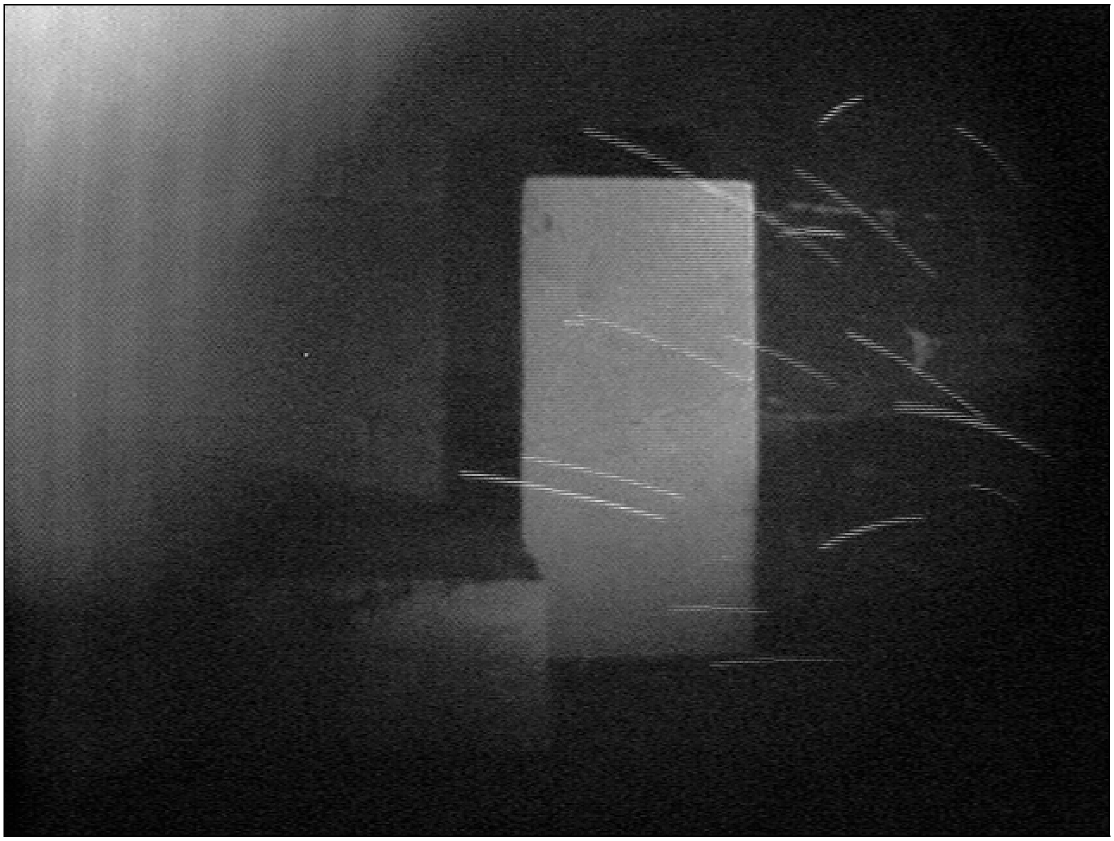


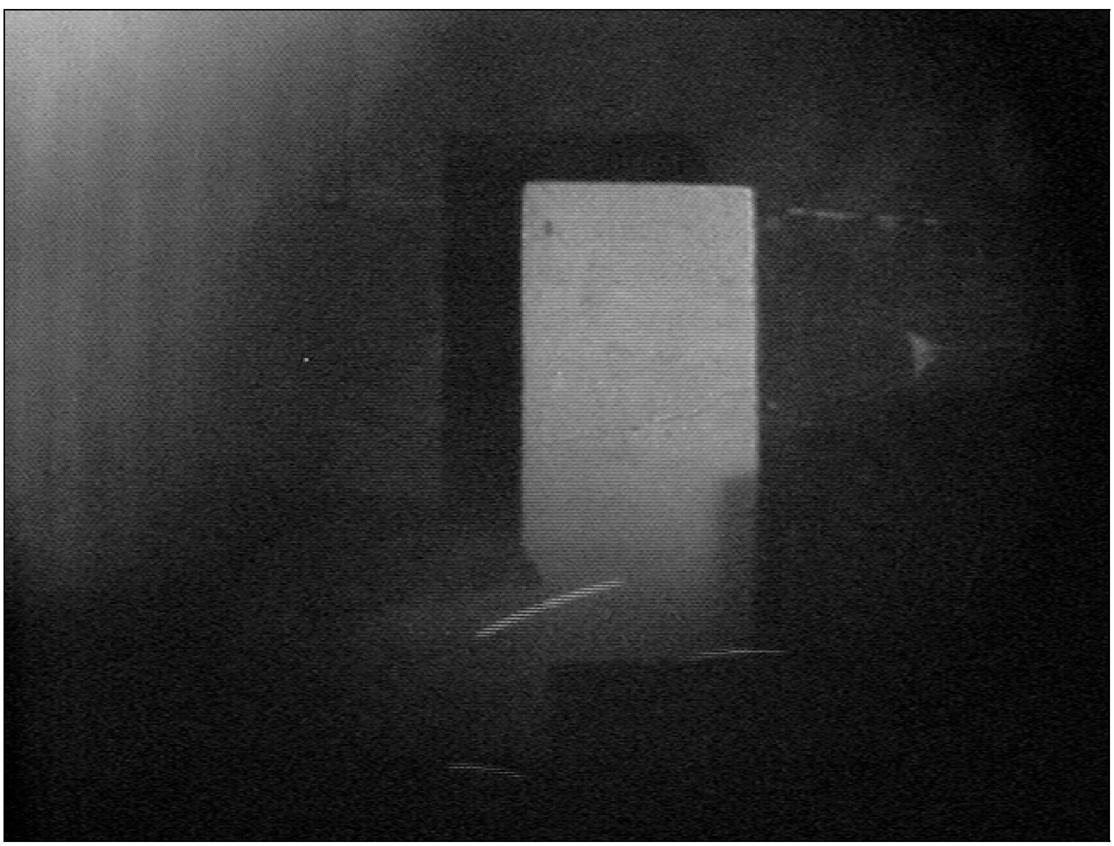


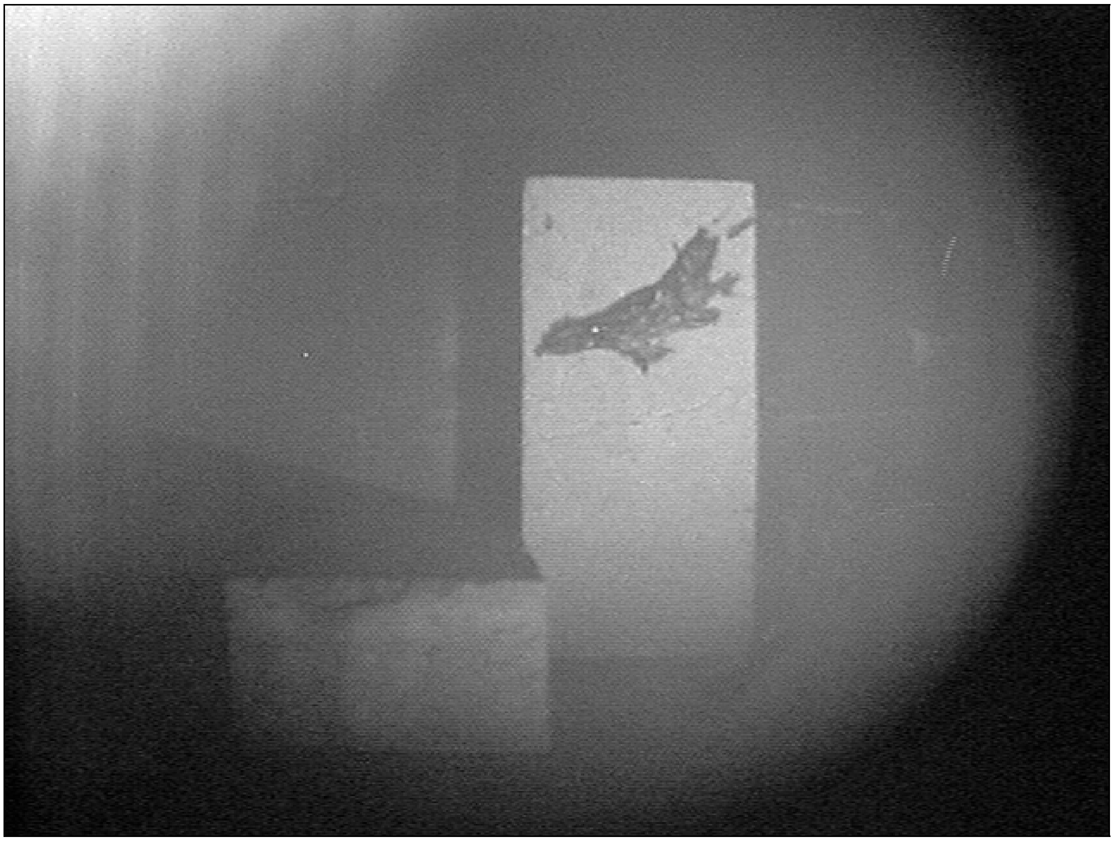


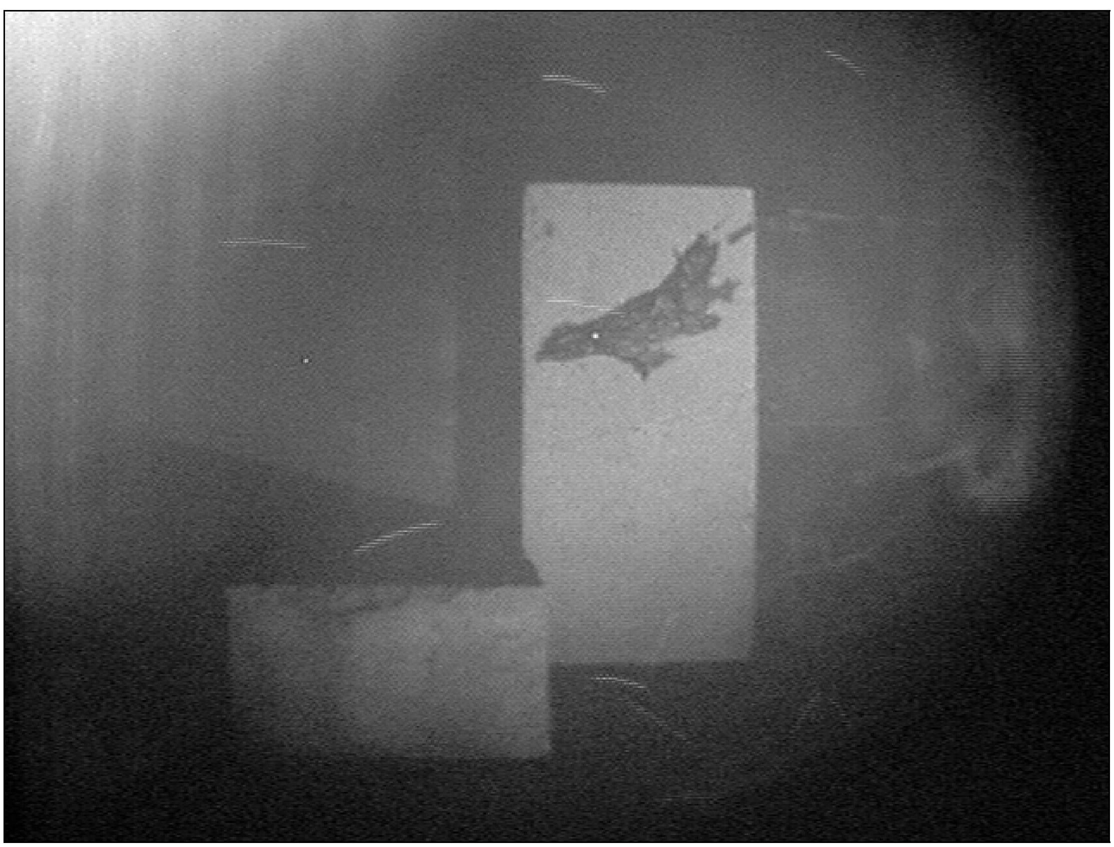






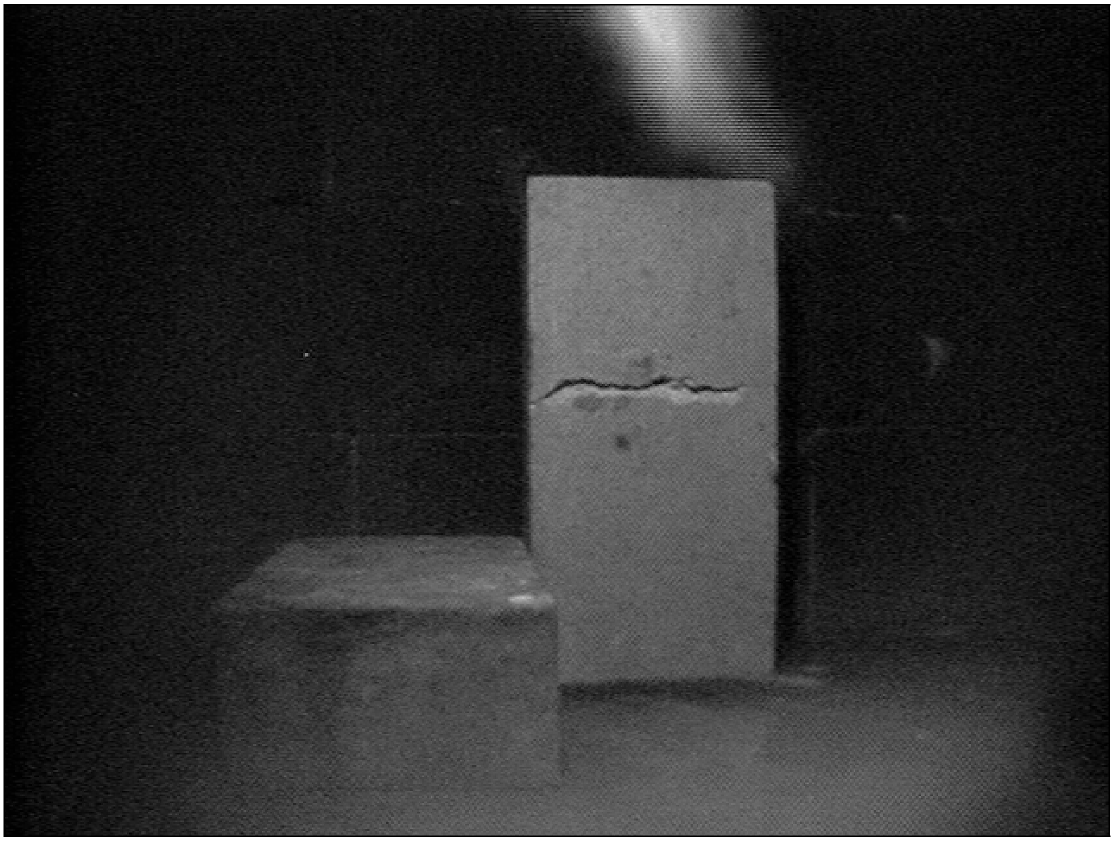


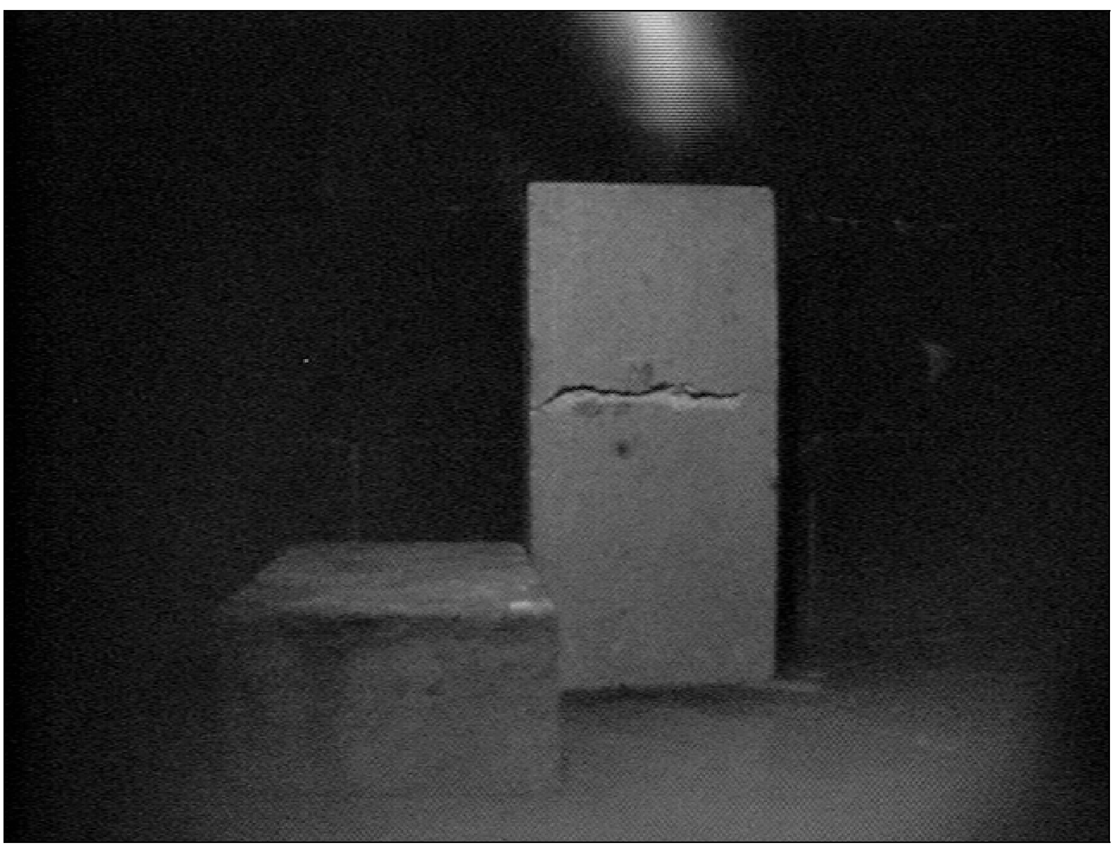


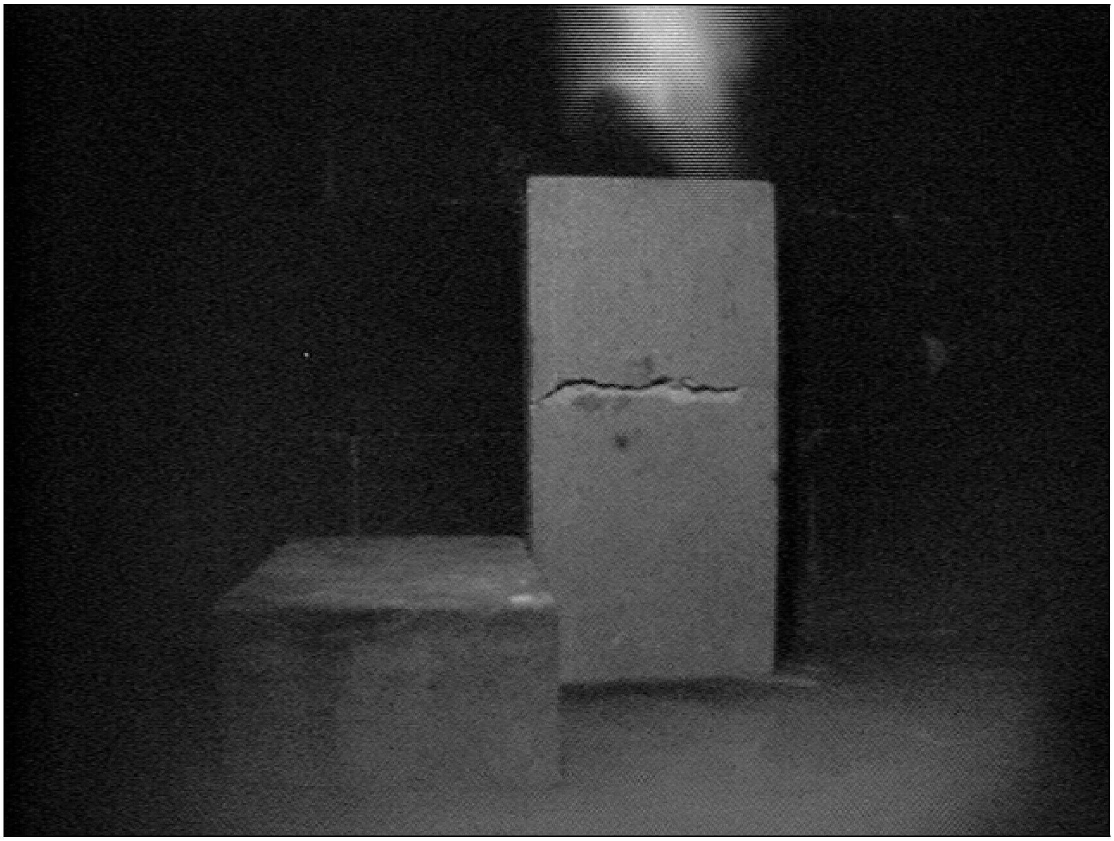


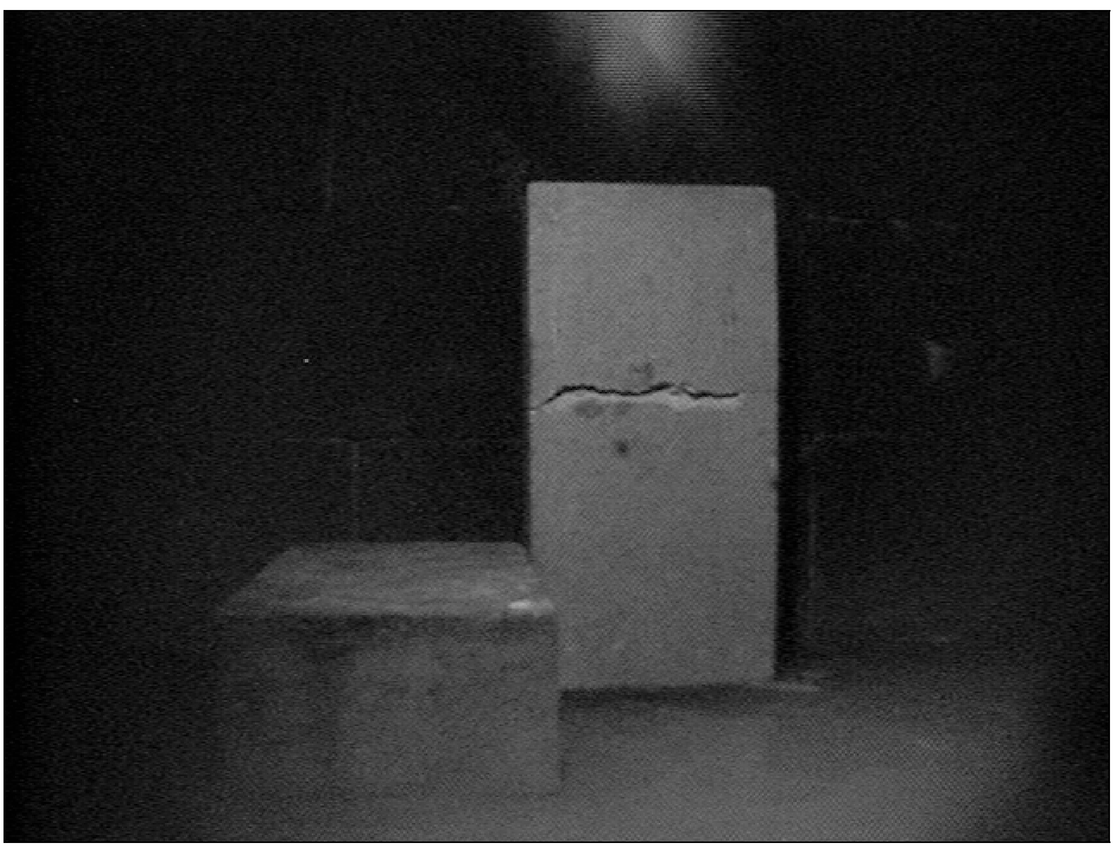
APPENDIX F

Combustion Light Source Images



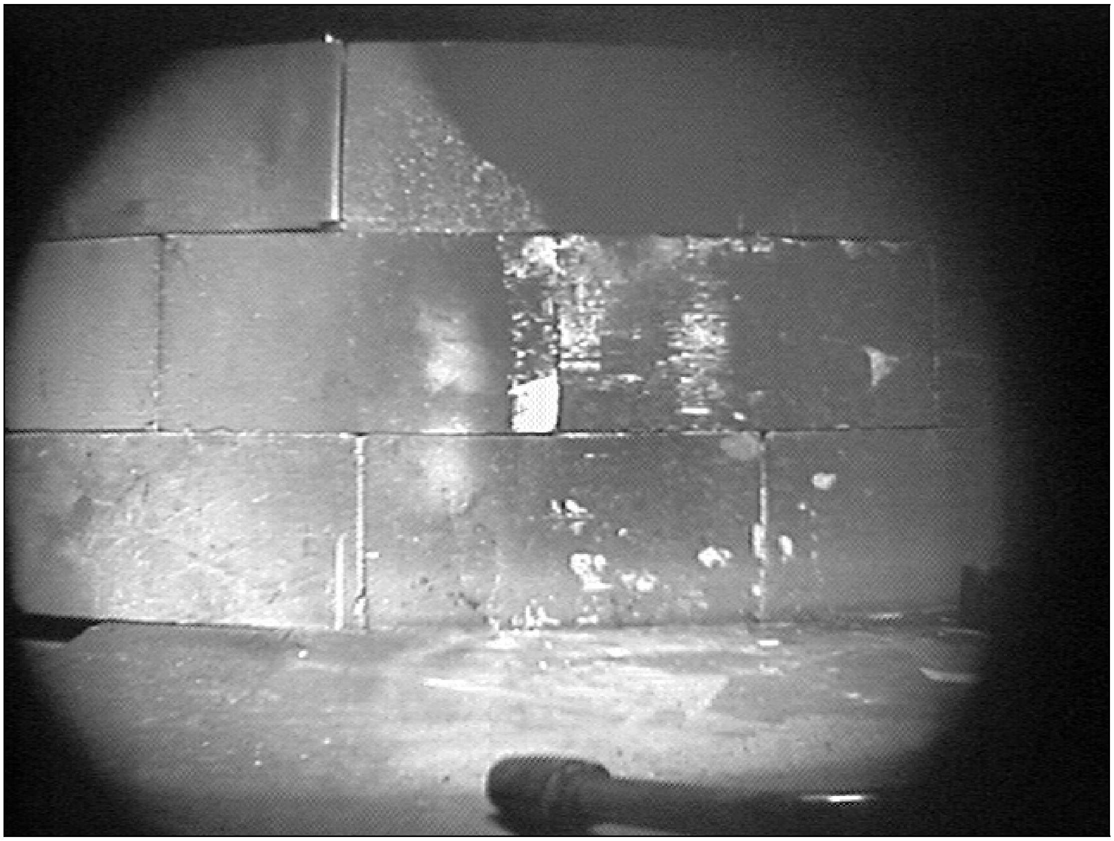


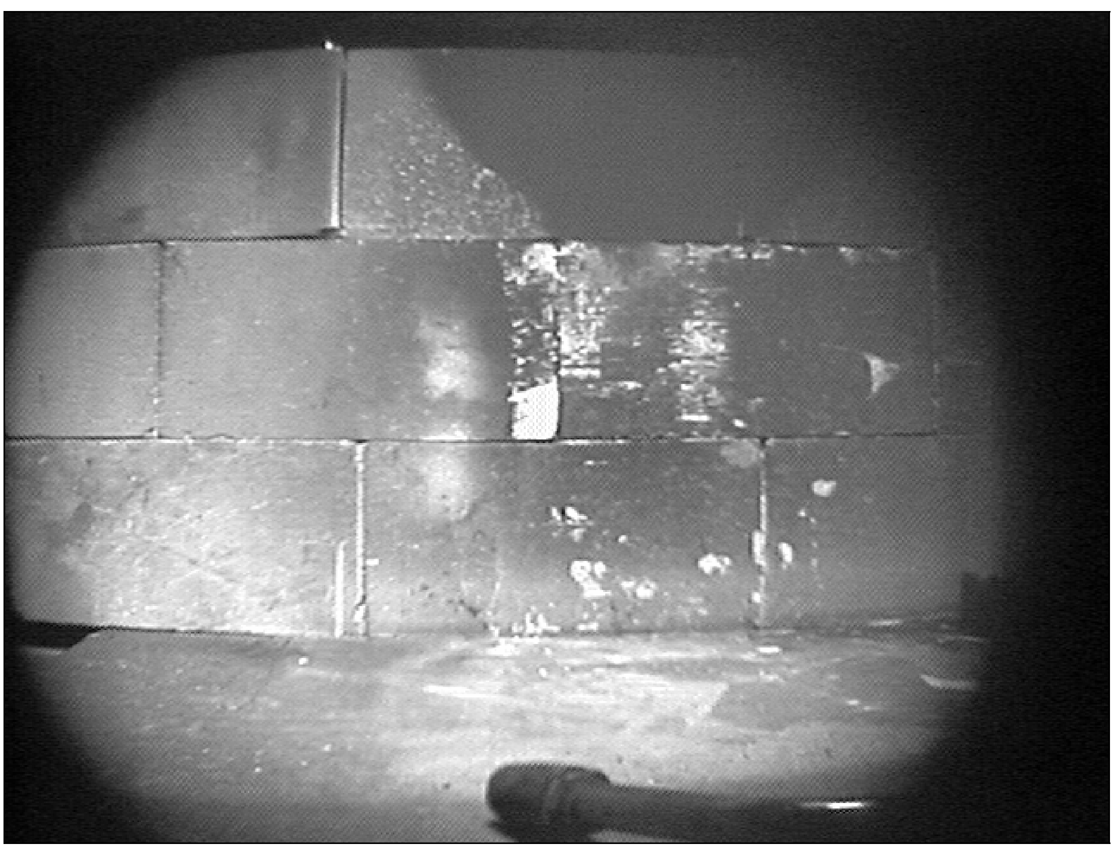


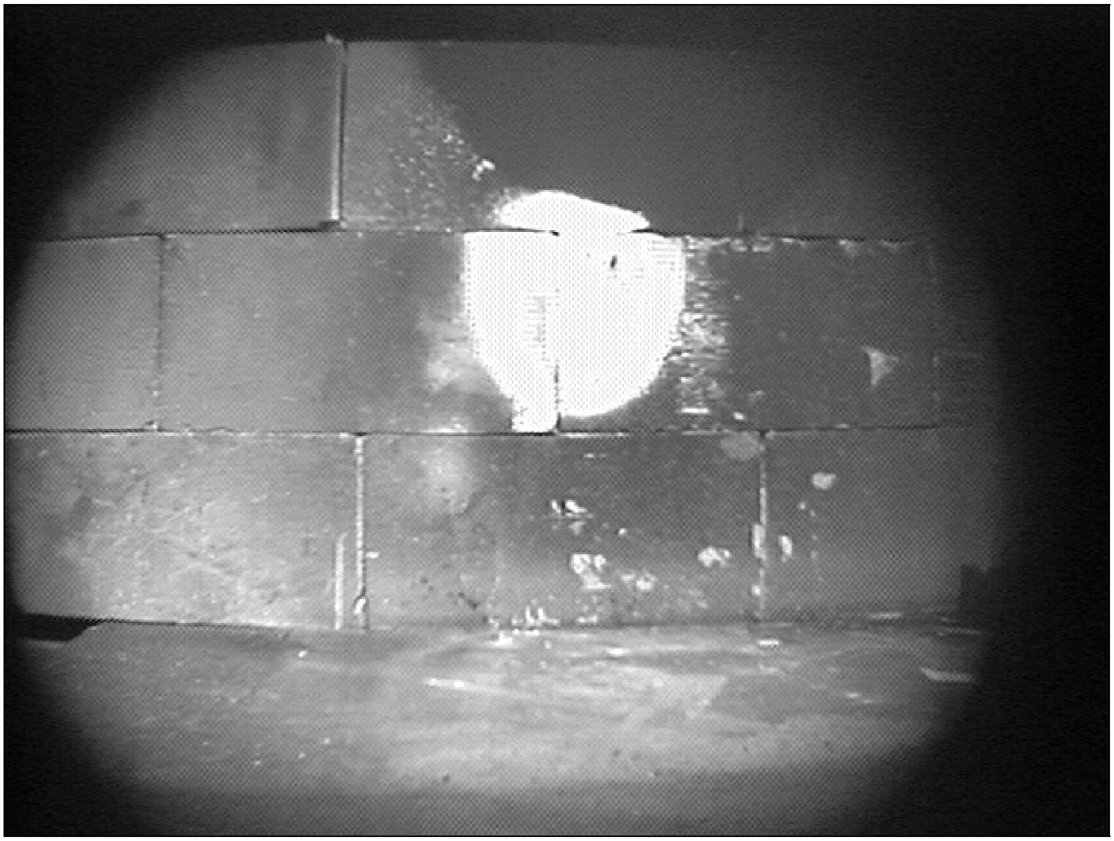


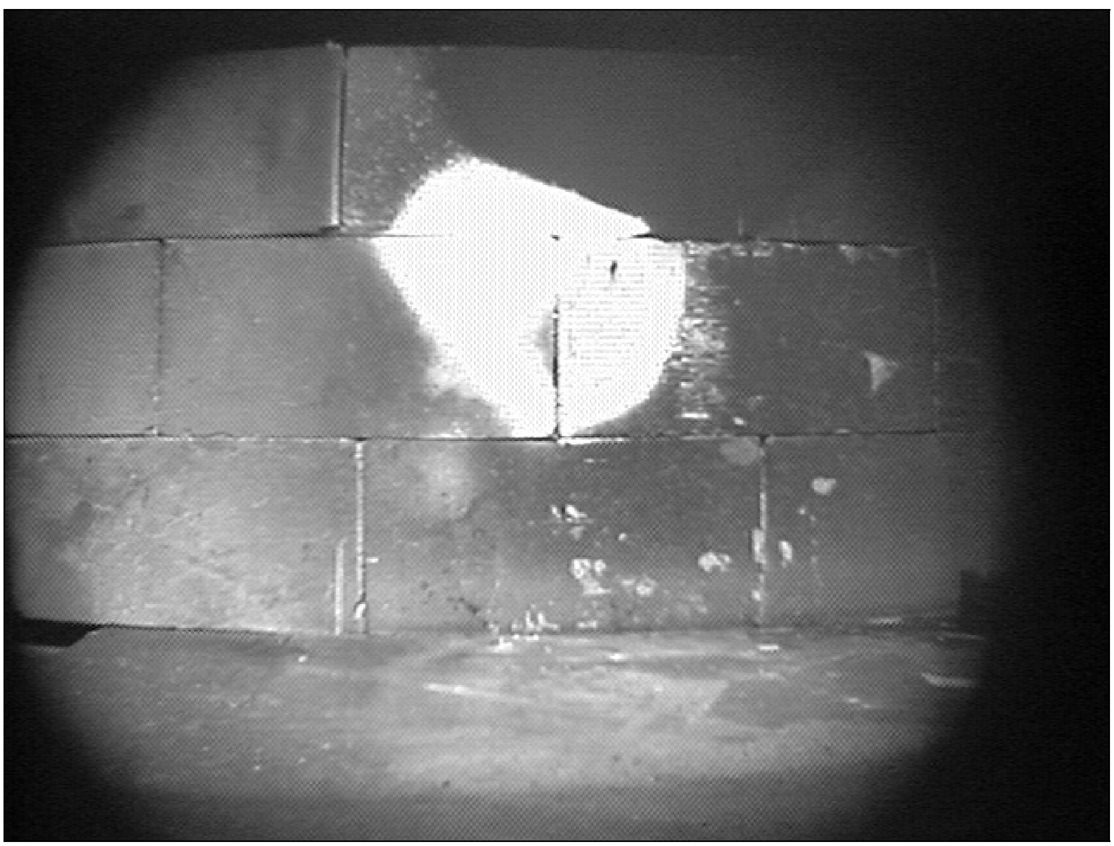
APPENDIX G

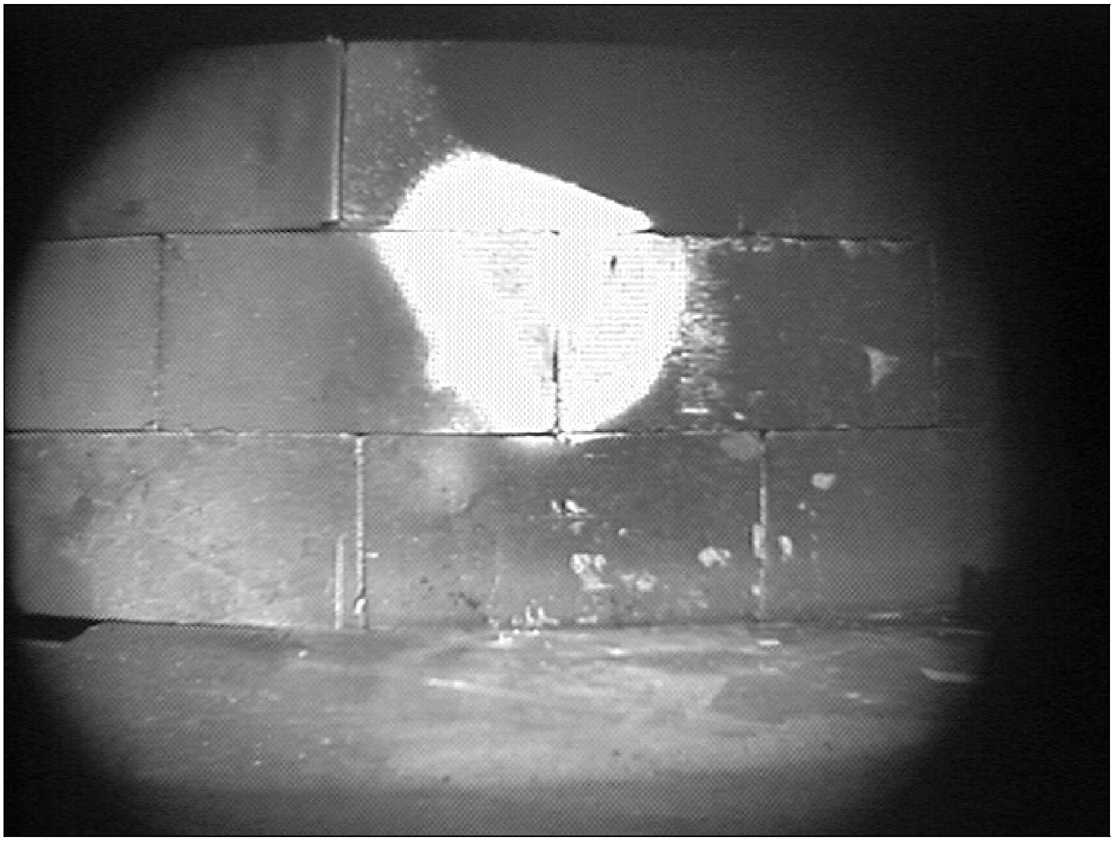
Hot Spot Recognition Images

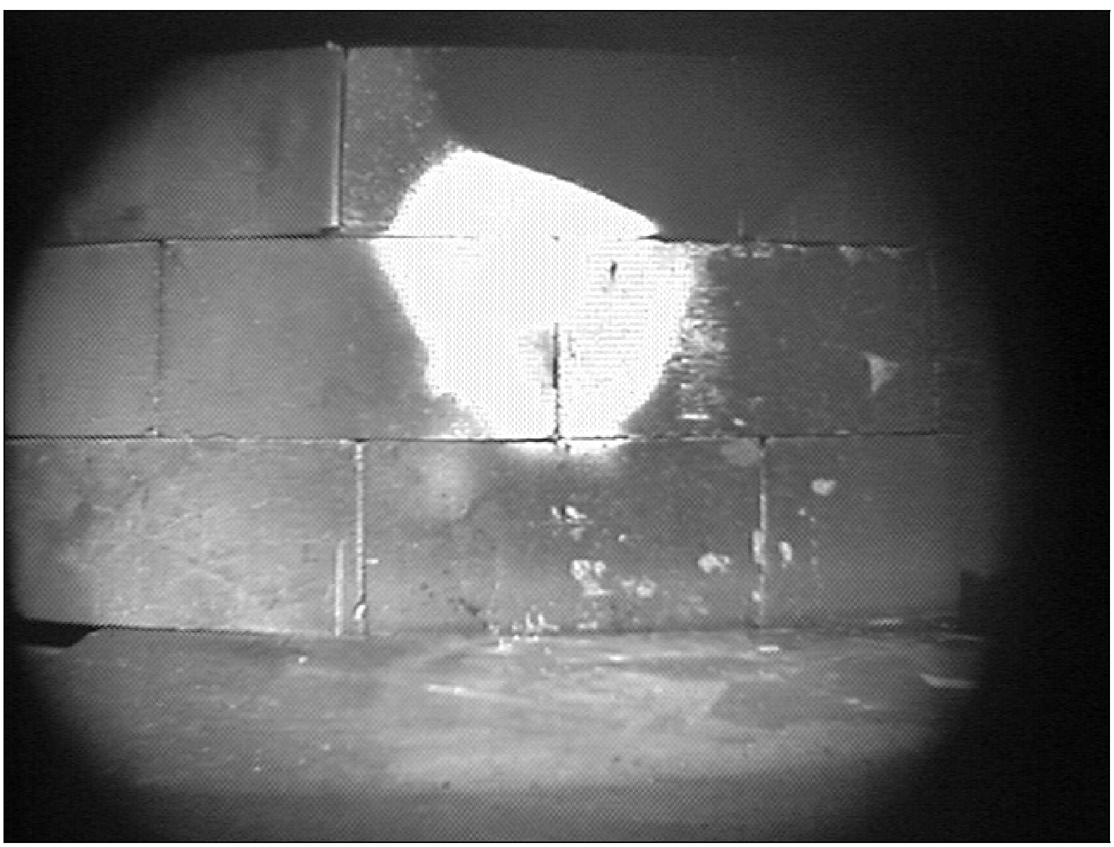






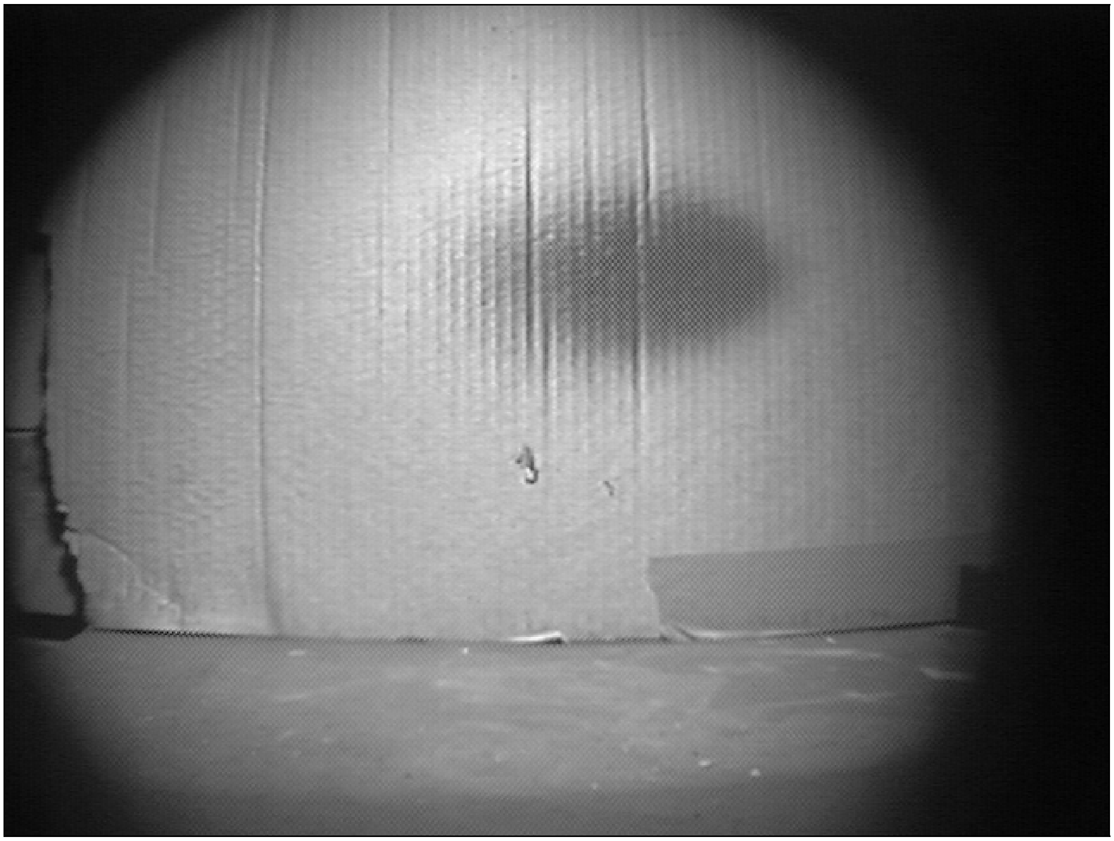


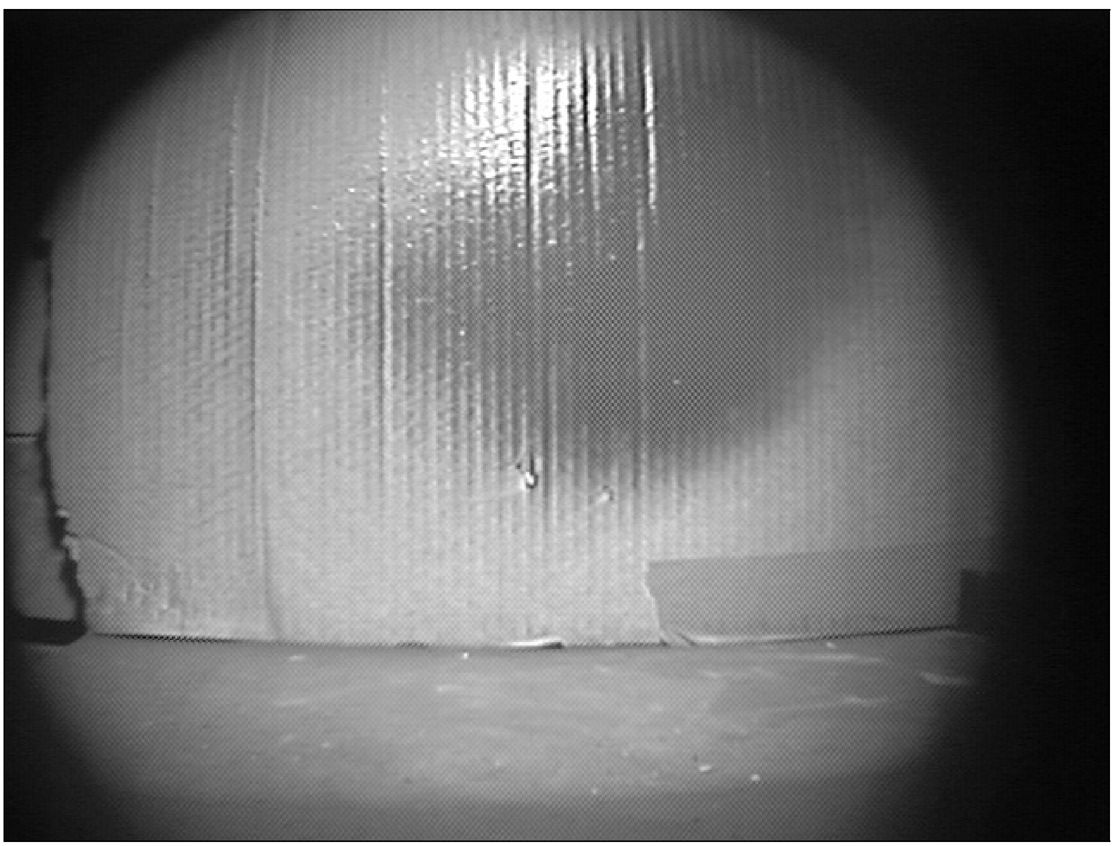


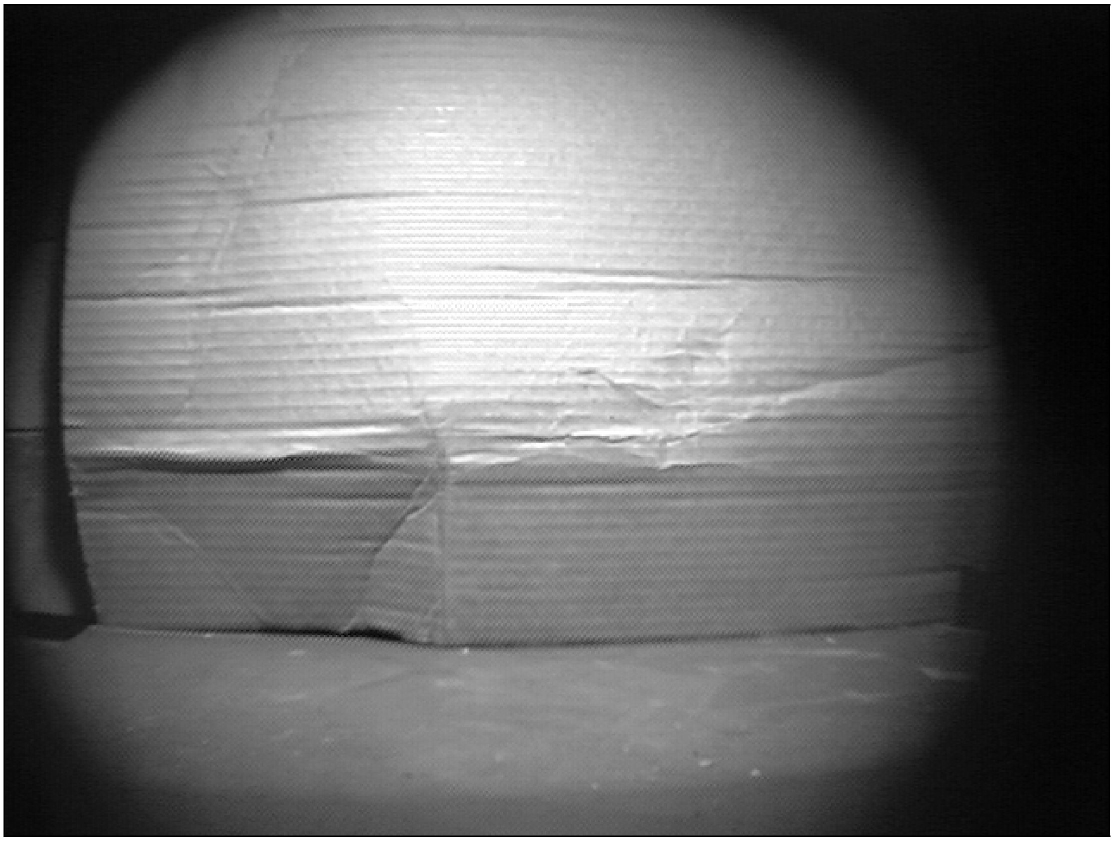


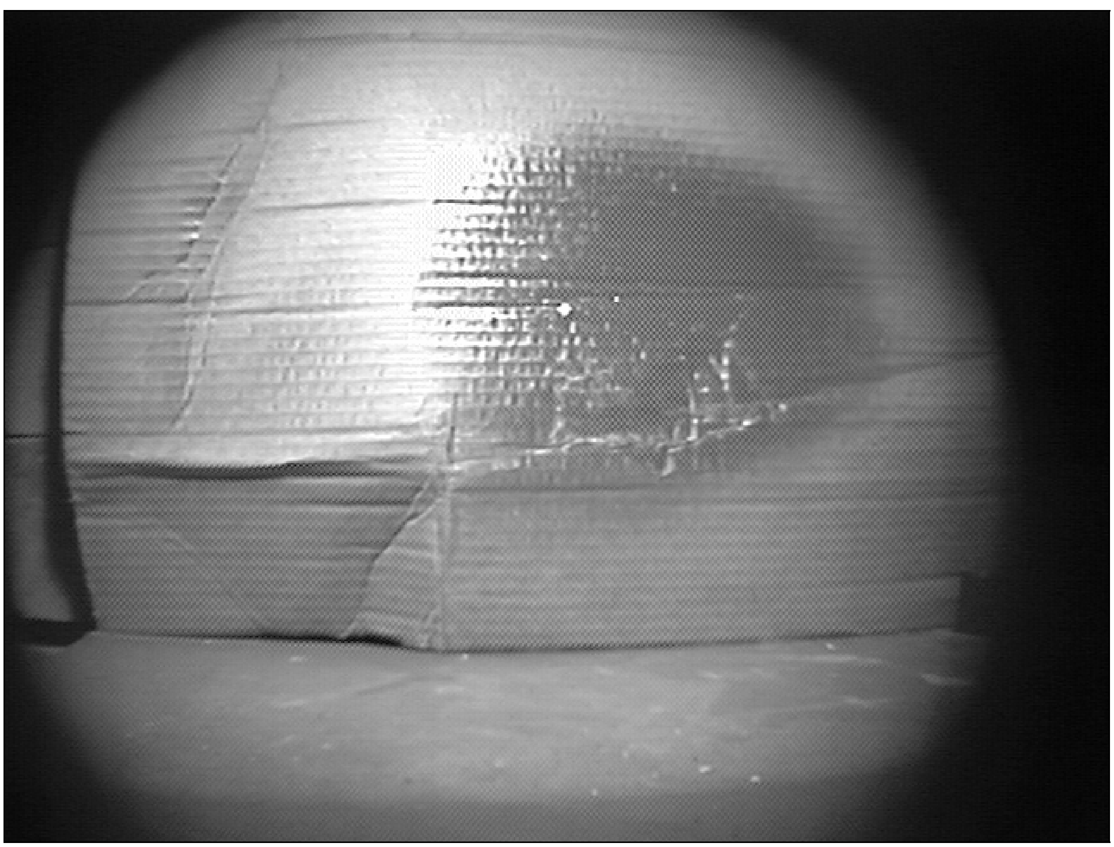
APPENDIX H

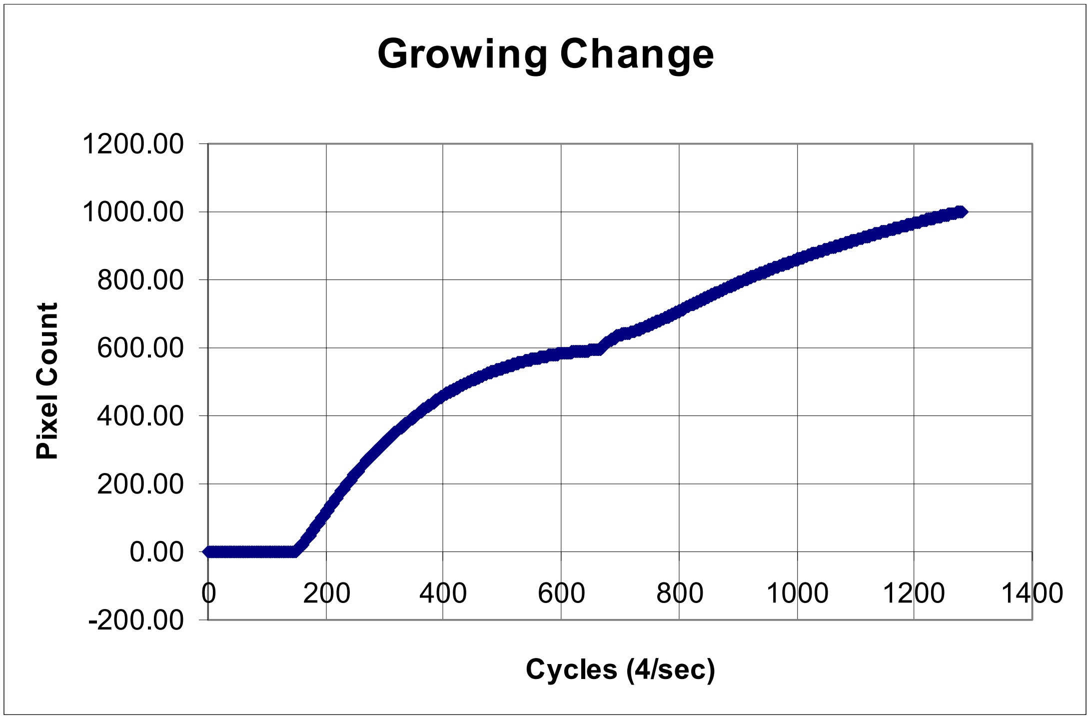
Streaming Image Mode Images and Data

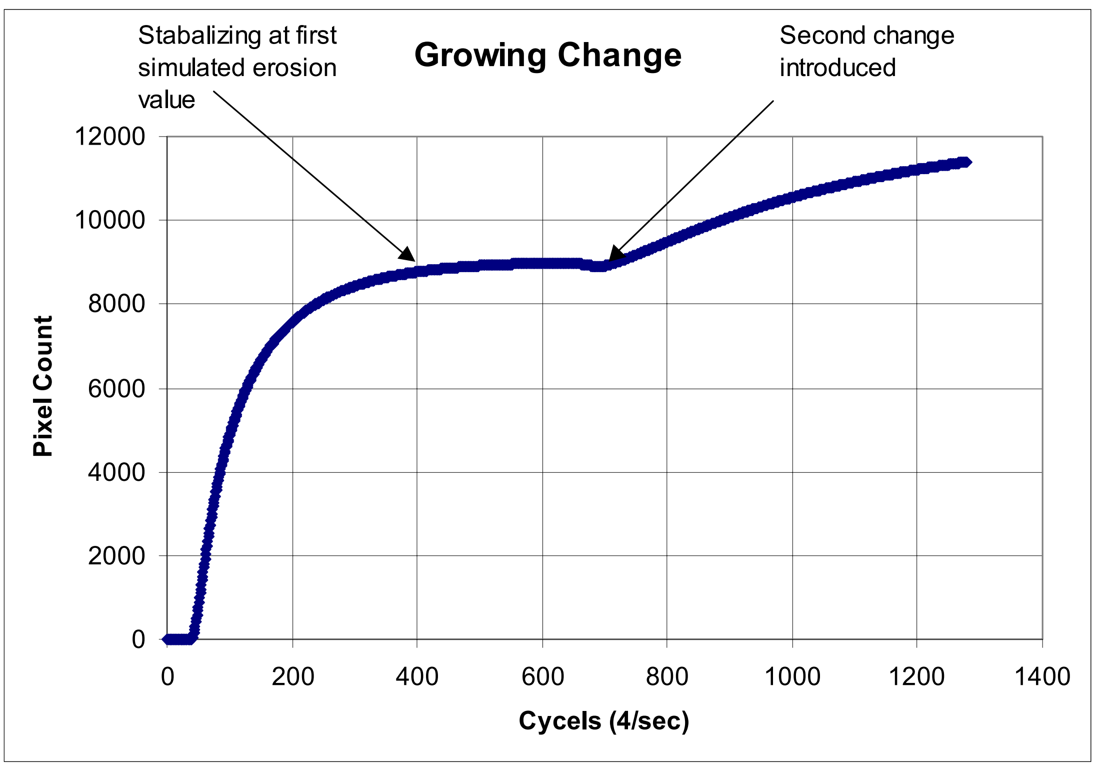









Growing Change
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
-200.00
0
200
400
600
800
1000
1200
1400
Pixel Count
Cycles (4/sec)


Growing Change
Stabalizing at first simulated erosion value
Second change introduced
12000
10000
8000
6000
4000
2000
0
0
200
400
600
800
1000
1200
1400
Pixel Count
Cycels (4/sec)